RI/RD-BD86-149

SPACE TRANSPORTATION BOOSTER ENGINE (STBE) CONFIGURATION STUDY

SECOND QUARTERLY REVIEW

11 SEPTEMBER 1986

Rockwell International
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STBE CONFIGURATION STUDY
SECOND QUARTERLY REVIEW
AGENDA

- INTRODUCTION .... F. KIRBY
- TASK 1 SUMMARY .... A. WEISS
- TASK 2 STATUS REVIEW
  - SUBSYSTEM OPTIMIZATION APPROACH .... A. WEISS
  - TURBOMACHINERY STUDIES .... A. EASTLAND
  - COMBUSTION DEVICES STUDIES .... P. MEHEGAN
  - THROTTLING ON-DESIGN/OFF-DESIGN STUDY .... W. BISSELL, D. NGUYEN
  - CONTROL SYSTEM AND HEALTH MONITOR STUDIES .... R. BREWSTER
- SUMMARY .... A. WEISS

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STUDY OBJECTIVES

THE OVERALL OBJECTIVE OF THIS ENGINE STUDY IS TO IDENTIFY CANDIDATE ENGINE CONFIGURATIONS WHICH ENHANCE VEHICLE PERFORMANCE AND PROVIDE OPERATIONAL FLEXIBILITY AT LOW COST. THE SPECIFIC OBJECTIVES ARE LISTED ON THIS CHART.

STUDY OBJECTIVES

- IDENTIFY AND EVALUATE CANDIDATE LOX/HC ENGINE CONFIGURATIONS FOR THE ADVANCED SPACE TRANSPORTATION SYSTEM FOR AN EARLY 1995 IOC AND A LATE 2000 IOC
- SELECT ONE OPTIMUM ENGINE FOR EACH TIME PERIOD
- PREPARE A CONCEPTUAL DESIGN FOR EACH CONFIGURATION
- DEVELOP A TECHNOLOGY PLAN FOR THE 2000 IOC ENGINE
- PREPARE PRELIMINARY PROGRAMMATIC PLANNING AND ANALYSIS FOR THE 1995 IOC ENGINE

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STBE STUDY TO BE ACCOMPLISHED IN 5 TASKS

IN TASK 1, THE REQUIREMENTS FOR THE STBE WERE DETERMINED AND 24 POTENTIAL CANDIDATE ENGINE CONFIGURATIONS IDENTIFIED AND SCREENED. THE 9 MOST PROMISING CANDIDATES ARE CARRIED INTO TASK 2

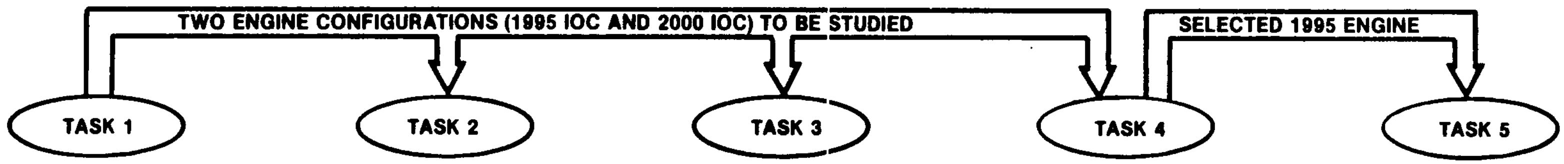
IN TASK 2 NINE (9) ENGINE CANDIDATES (6 FOR 1995 IOC AND 3 FOR 2000 IOC) WILL BE EVALUATED IN DEPTH TO DEFINE THE OPTIMUM MAJOR SUBSYSTEMS FOR EACH

IN TASK 3, THE TASK 1 AND TASK 3 CONFIGURATION EVALUATION PLAN AND SELECTION CRITERIA WERE DEVELOPED, SUBMITTED TO MSFC AND APPROVED. THE SELECTION OF ONE CANDIDATE EACH FOR 1995 AND 2000 IOC WILL BE ACCOMPLISHED IN TASK 3

IN TASK 4, CONCEPTUAL DESIGNS WILL BE PREPARED FOR BOTH THE 1995 AND 2000 IOC ENGINES. THE DESIGN FOR THE 1995 CONFIGURATION WILL BE IN SUFFICIENT DEPTH TO CONDUCT PRELIMINARY PROGRAMMATIC PLANNING

IN TASK 5, THE PRELIMINARY PROGRAMMATIC PLANNING AND ANALYSIS WILL BE COMPLETED.

STBE STUDY TO BE ACCOMPLISHED IN 5 TASKS



TASK 1

- IDENTIFICATION
  - — REQUIREMENTS
    - • STAS
    - • MSFC HLLV
  - — CANDIDATES
    - • THRUST RANGE
    - • CYCLES
    - • PROPELLANTS
    - • COOLANTS
  - — FEASIBILITY
    - • SCHEMATICS
    - • PERFORMANCE
    - • TECHNOLOGY
    - • JUDGEMENT
  - — ASSESSMENT
    - • PERFORMANCE
    - • LIFE CYCLE COSTS
    - • OPERABILITY

TASK 2

- EVALUATION
  - — TRADE STUDIES
    - • THRUST CHAMBER
    - • INJECTOR
    - • TURBINE DRIVE
    - • TURBOMACHINERY
    - • CONTROL
    - • HEALTH MONITORING
    - • MATERIALS
    - • FACILITIES
  - — SUPPORTING STUDIES
    - • LCC
    - • RISK
    - • RELIABILITY
    - • MAINTAINABILITY
    - • TECHNOLOGY
    - • PERFORMANCE

TASK 3

- SELECTION
  - — EVALUATION PLAN
    - • WEIGHTING FACTORS
    - • FIGURES OF MERIT
    - • SENSITIVITY STUDIES
    - • JUDGEMENTS
  - — SELECTION CRITERIA
    - • LCC
    - • RELIABILITY
    - • RISK
    - • MAINTAINABILITY

TASK 4

- DESIGN
  - — OPTIMIZATION
    - • SUBSYSTEM AND COMPONENTS
    - • STRUCTURE AND WEIGHT
    - • PERFORMANCE
  - — DRAWINGS
    - • LAYOUTS
    - • INTERFACE
    - • COMPONENT DEFINITION
    - • LONG LEAD ITEMS
  - — SUPPORTING STUDIES
    - • FMEA
    - • RISK
    - • CHECKOUT, SERVICING, GSE, REFURB
    - • HAZARDS AND SAFETY

TASK 5

- PROGRAMMATICS
  - — SCHEDULES
    - • OVERALL DDT&E
    - • SUPPORTING
  - — FACILITIES
    - • TEST
    - • MANUFACTURING
    - • ENGINEERING
    - • ASSEMBLY
  - — WBS AND DICTIONARY
    - • STAS FORMAT
  - — COST
    - • DDT&E
    - • PRODUCTION
    - • OPERATIONS
    - • FACILITIES
  - — ENVIRONMENTAL IMPACT

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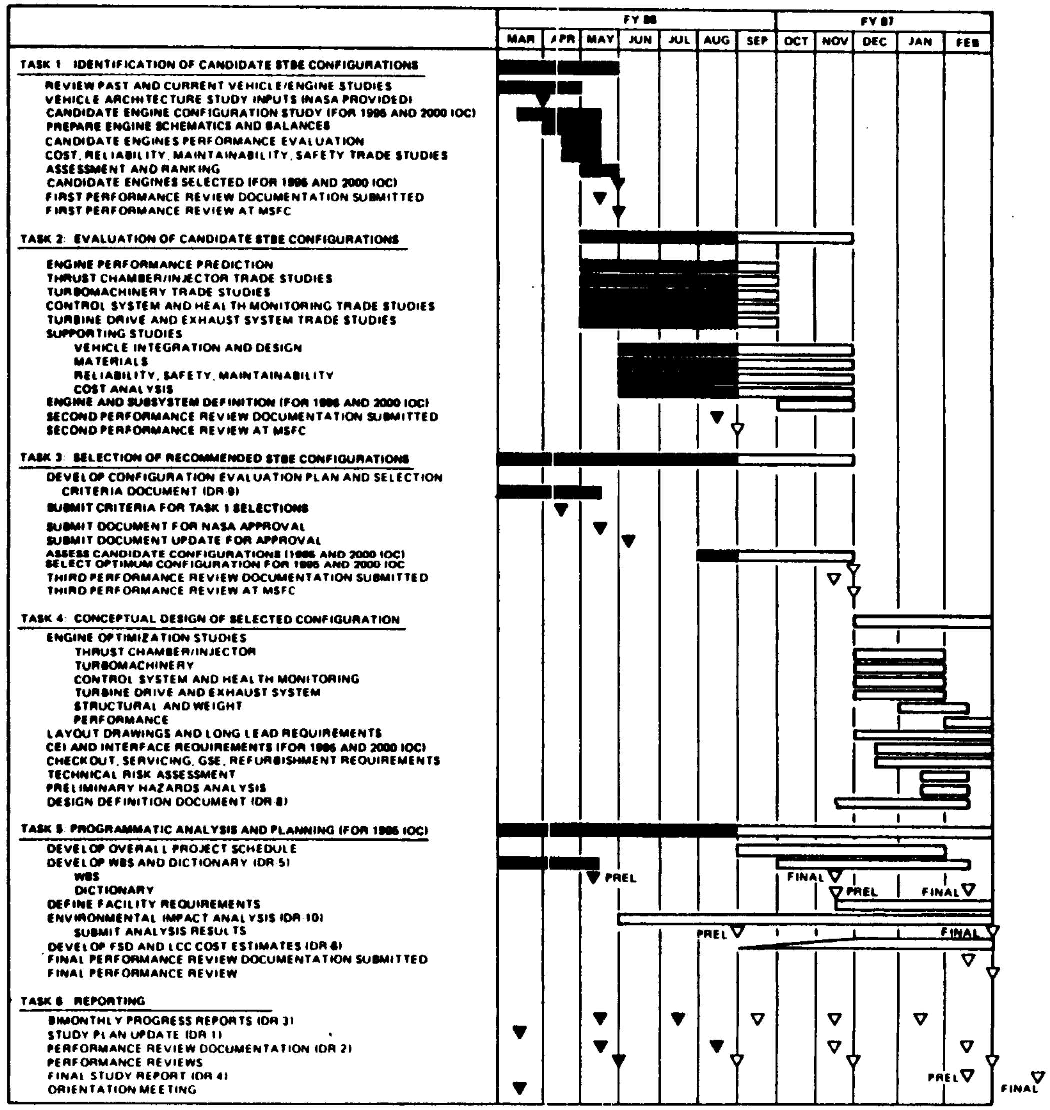
STBE PROGRAM SCHEDULE

THE STBE CONFIGURATION STUDY IS ON SCHEDULE.

STBE PROGRAM SCHEDULE



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STBE CONFIGURATION STUDY SECOND QUARTERLY REVIEW

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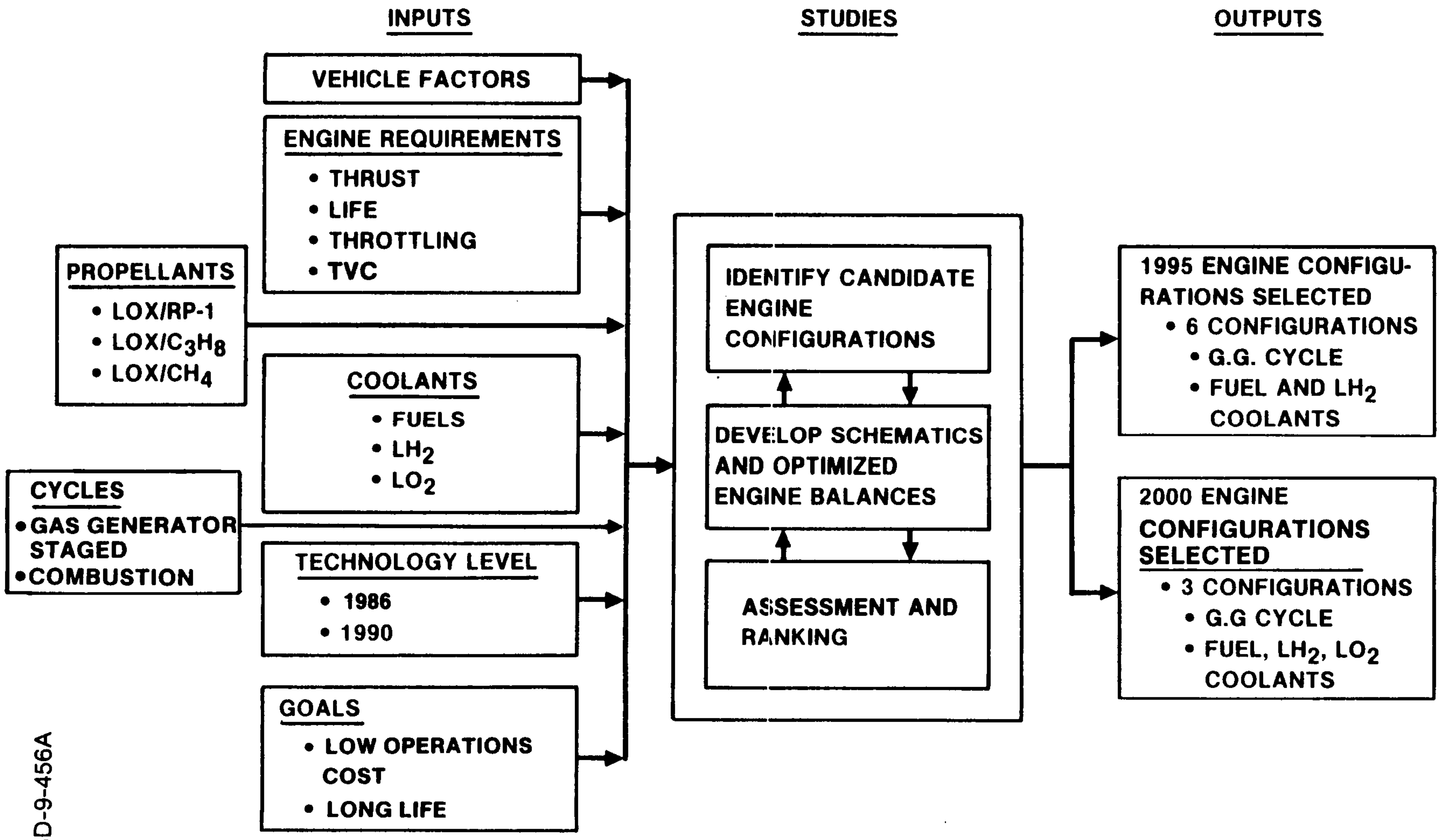
TASK 1 - IDENTIFICATION OF CANDIDATE STBE CONFIGURATIONS

THIS CHART SHOWS THE FLOW DIAGRAM FOR THE TASK 1 EFFORT. THE INPUTS WERE DERIVED FROM NASA-MSFC, STAS STUDIES AND PRIOR ROCKETDYNE IN-HOUSE STUDIES. THEY WERE USED TO IDENTIFY 24 CANDIDATE ENGINE CONFIGURATIONS. THESE WERE REDUCED TO 19 AFTER A PRELIMINARY TECHNICAL EVALUATION. ENGINE FLOW SCHEMATICS AND PERFORMANCE OPTIMIZATION BALANCES WERE THEN PREPARED FOR THE 19 ENGINE CONFIGURATIONS. AN ASSESSMENT AND RANKING PROCESS WHICH CONSIDERED ENGINE RELIABILITY, WEIGHT, LIFE CYCLE COST, PROPELLANT BULK DENSITY AND RISK WAS USED TO SELECT 6 CONFIGURATIONS TO SUPPORT A 1995 IOC AND 3 CONFIGURATIONS TO SUPPORT A 2000 IOC. THESE 9 CONFIGURATIONS WERE CARRIED INTO TASK 2.

TASK 1 — IDENTIFICATION OF CANDIDATE STBE CONFIGURATIONS



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SPACE TRANSPORTATION BOOSTER ENGINE REQUIREMENTS

THE PRIMARY ENGINE REQUIREMENTS WERE INPUT TO THE STBE STUDY CONTRACTORS BY NASA-MSFC. THE REQUIREMENTS FOR MAIN CHAMBER PRESSURE AND PUMP INLET PRESSURE WERE DEVELOPED BY ROCKETDYNE FROM DISCUSSIONS WITH THE STAS CONTRACTORS AND IN-HOUSE STUDIES. A HIGH P_c, HIGH PERFORMANCE ENGINE ENHANCES VEHICLE PERFORMANCE AND COST. ELIMINATION OF THE BOOST PUMPS SIMPLIFIES THE TURBOMACHINERY.

SPACE TRANSPORTATION BOOSTER ENGINE REQUIREMENTS

- **NASA-MSFC SUPPLIED**
  - RATED THRUST = 625K @ SL
  - MAXIMUM THRUST = 750K (@ SL)

  - ENGINE LIFE @ RATED THRUST
    - 25 MISSIONS TO OVERHAUL
    - 100 MISSIONS DESIGN LIFE

  - FUEL = T.B.D.
  - THROTTLE RANGE = + 0, -20%
  - BURN TIME = 160 SEC MAX
  - GIMBAL ANGLE = 6 DEGREE SQUARE PATTERN
  - CLOSED LOOP THRUST/MR CONTROL

- **ROCKETDYNE DEVELOPED**
  - MAIN COMBUSTION CHAMBER PRESSURE OPTIMIZED FOR MAXIMUM VACUUM ISP
  - PUMP INLET PRESSURE SUFFICIENT TO NOT REQUIRE BOOST PUMPS

CANDIDATE ENGINES FOR TASK 1
STUDY IDENTIFIED

TWENTY-FOUR CANDIDATE CONFIGURATIONS WERE IDENTIFIED FOR EVALUATION. HALF WERE DEFINED WITH 1986 TECHNOLOGY AND THE OTHER HALF WITH 1990 TECHNOLOGY. FIVE CONFIGURATIONS WERE THEN REJECTED BY AN ENGINEERING PRE-SCREEN.

CANDIDATE ENGINES FOR TASK 1 STUDY IDENTIFIED

- **24 CANDIDATES CONSIDERED**
  - 12 TO SUPPORT A 1995 LAUNCH DATE
  - 12 TO SUPPORT A 2000 LAUNCH DATE
- **5 OF 24 CANDIDATES REJECTED DUE TO LACK OF FEASIBILITY OR ADVANTAGE**
- **2 THRUST LEVELS EVALUATED FOR 1995 CANDIDATES**
  - 750K AND 1500K
  - 1500K FOR REFERENCE ONLY — NOT USED IN SCREENING PROCESS

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CANDIDATE STBE CONFIGURATIONS FOR TASK 1

THESE WERE THE 19 CANDIDATES THAT WERE EVALUATED. OF THESE, 3 WERE AT 1500 Klb THRUST AND ARE FOR COMPARISON PURPOSES ONLY. THIS LEFT 16 ENGINES TO BE EVALUATED AND SCREENED DOWN TO THE 9 THAT WERE RECOMMENDED FOR TASK 2 COMPONENT EVALUATION.

CANDIDATE STBE CONFIGURATIONS FOR TASK 1

ENGINE NUMBER	SEA LEVEL THRUST	CYCLE	I.O.C. DATE	INJECTOR PROPELLANTS	COOLANT	TURBINE DRIVE*	COMMENT
1	750K	G.G.	1995	LOX/RP-1	RP-1	LOX/RP-1	FUEL COOLED GG
2	750K	G.G.	1995	LOX/C_3H_8	C_3H_8	LOX/C_3H_8	
3	750K	G.G.	1995	LOX/CH_4	CH_4	LOX/CH_4	
4	750K	G.G.	1995	LOX/RP-1	LH_2	LOX/LH_2	LH_2 COOLED GG
5	750K	G.G.	1995	LOX/C_3H_8	LH_2	LOX/LH_2	
6	750K	G.G.	1995	LOX/CH_4	LH_2	LOX/LH_2	
7	750K	S.C.	1995	LOX/CH_4	CH_4	LOX/CH_4	FUEL COOLED SC
8	1500K	G.G.	1995	LOX/RP-1	RP-1	LOX/RP-1	HIGHER THRUST
9	1500K	G.G.	1995	LOX/C_3H_8	C_3H_8	LOX/C_3H_8	
10	1500K	G.G.	1995	LOX/CH_4	CH_4	LOX/CH_4	
11	750K	G.G.	2000	LOX/RP-1	LO_2	LOX/RP-1	LOX COOLED GG
12	750K	G.G.	2000	LOX/C_3H_8	LO_2	LOX/C_3H_8	
13	750K	G.G.	2000	LOX/CH_4	LO_2	LOX/CH_4	
14	750K	S.C.	2000	LOX/C_3H_8	LO_2	LOX/C_3H_8	LOX COOLED SC
15	750K	S.C.	2000	LOX/CH_4	LO_2	LOX/CH_4	
16	750K	S.C.	2000	LOX/C_3H_8	C_3H_8	LOX/C_3H_8	FUEL COOLED SC WITH MIXED PREBURNERS
17	750K	S.C.	2000	LOX/CH_4	CH_4	LOX/CH_4	
18	750K	G.G.	2000	LOX/RP-1/LH_2	LH_2	LOX/LH_2	TRIPROPELLANT
19	750K	G.G.	2000	LOX/C_3H_8/LH_2	LH_2	LOX/LH_2	

* FUEL-RICH UNLESS OTHERWISE NOTED IN COMMENTS

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SUMMARY OF TECHNICAL ENGINE DATA

THIS CHART SUMMARIZES THE TECHNICAL (NON-COST) DATA USED IN DETERMINING THE LIFE CYCLE COST PARAMETERS FOR THE SCREENING PROCESS.

SUMMARY OF TECHNICAL ENGINE DATA

ENGINE NUMBER	VACUUM I_{SP}, SEC	WEIGHT, W, LB	PROPELLANT BULK DENSITY, ρ_B, LB/FT3	COMPLEXITY FACTOR	PROBABITY OF SUCCESS	TECHNICAL LEVEL
1995 ENGINE CANDIDATES						
REFERENCE	304.5	9308x2*	63.3	14	1.00	9
1	329.2	8000	63.3	13	.95	6
2	344.7	8090	61.6	16	.75	2
3	350.0	8370	50.0	16	.95	3
4	344.7	7800	56.4	16	.95	6
5	353.5	7760	55.1	16	.75	3
6	355.2	7810	46.9	17	.95	3
7	362.7	10400	51.0	21	.90	5
2000 ENGINE CANDIDATES						
11	343.1	7880	63.4	13	.85	4
12	350.2	8360	61.7	16	.75	3
13	355.3	8490	50.4	16	.85	4
14	360.2	10250	62.5	23	.70	2
15	369.5	10860	51.6	23	.85	5
16	368.9	12760	62.5	26	.70	2
17	376.8	13400	51.6	26	.75	4
18	360.5	7910	52.1	20	.65	1
19	365.8	7880	51.0	20	.65	1

* SINCE THE F-1 HAS 1500 KLBS S.L. THRUST, BUT THE STBE ENGINES SHOWN HERE ALL HAVE 750 KLBS S.L. THRUST, THE F-1 ENGINE WEIGHT WAS HALVED TO BE COMPARABLE.

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SUMMARY OF ENGINE COST DATA

THE PRODUCTION, DEVELOPMENT, CERTIFICATION, AND O&S COSTS, ESTIMATED FOR THE SIXTEEN STBE CANDIDATES IN THE TWO IOC GROUPS ARE LISTED. THE COSTS WERE OBTAINED USING ROCKETDYNE'S SUITE OF PARAMETRIC COST MODELS WITH THE PRINCIPAL INPUT PARAMETERS AS SHOWN. ALL ENGINES ARE AT THE 750 KLBS SL THRUST LEVEL, CORRESPONDING TO ABOUT 850 KLBS VACUUM THRUST. THE LAST COLUMN, ENGINE LCC, IS THE SUM OF ALL COST ELEMENTS.

SUMMARY OF ENGINE COST DATA — FY 86 $

ENGINE NUMBER	SEA LEVEL THRUST KLBS	CYCLE	PROPELLANTS	COOLANT	CHAMBER PRESSURE PSIA	PRODUCTION COST T(1) $M	PRODUCTION COST TOTAL-48 $B	DEVEL-OPMENT COST $B	CERTIFI-CATION COST $B	OPERATIONS & SUPPORT COST $B	ENGINE LCC $B
1995 ENGINE CANDIDATES											
REF.	1500	GAS GEN	LOX/RP-1	RP-1	1000	$15.5	$0.260	$0.100	$0.047	$1.471	$1.878
1	750	GAS GEN	LOX/RP-1	RP-1	2350	11.9	0.370	0.907	0.089	0.994	2.360
2	750	GAS GEN	LOX/C3H8	C3H8	3410	16.2	0.504	1.234	0.122	1.218	3.078
3	750	GAS GEN	LOX/CH4	CH4	3500	19.3	0.600	1.468	0.145	1.379	3.592
4	750	GAS GEN	LOX/RP-1	LH2	3120	14.7	0.456	1.340	0.110	1.138	3.044
5	750	GAS GEN	LOX/C3H8	LH2	3120	18.9	0.586	1.717	0.141	1.355	3.799
6	750	GAS GEN	LOX/CH4	LH2	2630	21.6	0.672	1.987	0.162	1.499	4.320
7	750	STG COMB	LOX/CH4	CH4	3040	24.7	0.768	1.881	0.185	1.660	4.494
2000 ENGINE CANDIDATES											
11	750	GAS GEN	LOX/RP-1	LO2	3380	13.3	0.413	1.011	0.100	1.066	2.589
12	750	GAS GEN	LOX/C3H8	LO2	3850	16.5	0.514	1.258	0.124	1.234	3.130
13	750	GAS GEN	LOX/CH4	LO2	3770	19.3	0.600	1.468	0.145	1.379	3.592
14	750	STG COMB	LOX/C3H8	LO2	3460	20.9	0.648	1.585	0.156	1.459	3.848
15	750	STG COMB	LOX/CH4	LO2	3700	25.5	0.792	1.573	0.191	1.700	4.256
16	750	STG COMB	LOX/C3H8	C3H8	6420	23.5	0.730	1.782	0.176	1.595	4.283
17	750	STG COMB	LOX/CH4	CH4	6120	27.8	0.864	2.115	0.209	1.821	5.009
18	750	GAS GEN	LOX/RP-1/LH2	LH2	4000	15.5	0.480	1.406	0.116	1.178	3.180
19	750	GAS GEN	LOX/C3H8/LH2	LH2	4000	19.3	0.600	1.761	0.145	1.379	3.885

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SUMMARY OF VEHICLE LIFE CYCLE COST ELEMENTS

THE SIX INDIVIDUAL LCC ELEMENTS WHICH, WHEN SUMMED, RESULT IN THE OVERALL COST SCREENING CRITERION, $\Sigma(\Delta LCC_V)$, ARE LISTED FOR ALL ENGINE CANDIDATES OF THE TWO IOC GROUPS.

SUMMARY OF VEHICLE LIFE CYCLE COST ELEMENTS — FY 86 $B

ENGINE NUMBER	SPECIFIC IMPULSE	WEIGHT	LCC	RELIABILITY	DENSITY	RISK	TOTAL LIFE CYCLE COST IMPACT
1995 ENGINE CANDIDATES							
REF. 1	($0.864)	($0.562)	$0.482	($0.043)	$0.000	$0.005	($0.983)
2	(1.407)	(0.524)	1.200	0.067	0.088	0.216	(0.359)
3	(1.593)	(0.403)	1.714	0.122	0.692	0.037	0.568
4	(1.407)	(0.648)	1.166	0.040	0.359	0.007	(0.484)
5	(1.715)	(0.666)	1.921	0.114	0.426	0.215	0.295
6	(1.774)	(0.644)	2.442	0.185	0.853	0.050	1.111
7	(2.037)	0.470	2.616	0.363	0.640	0.038	2.089
2000 ENGINE CANDIDATES							
11	(1.351)	(0.614)	0.711	(0.022)	(0.005)	0.045	(1.235)
12	(1.599)	(0.408)	1.252	0.073	0.083	0.157	(0.442)
13	(1.778)	(0.352)	1.714	0.122	0.671	0.066	0.443
14	(1.949)	0.405	1.970	0.332	0.042	0.333	1.133
15	(2.275)	0.667	2.378	0.454	0.608	0.047	1.880
16	(2.254)	1.484	2.405	0.195	0.042	0.374	2.246
17	(2.531)	1.760	3.131	0.652	0.608	0.159	3.779
18	(1.960)	(0.601)	1.302	0.125	0.582	0.492	(0.060)
19	(2.146)	(0.614)	2.007	0.211	0.640	0.616	0.714

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TASK 1 ENGINES SELECTED

THE ENGINE CANDIDATES ARE RANKED ACCORDING TO THEIR OVERALL COST CRITERION, $\Sigma(\Delta LCC_V)$. THE MINIMUM VALUE OF THE OVERALL COST CRITERION LEADS TO THE HIGHEST RANKED ENGINE.

TASK I ENGINES SELECTED

RANK	ENGINE NUMBER	TOTAL LIFE CYCLE COST IMPACT	CYCLE	PROPELLANTS	COOLANT
1995 ENGINE CANDIDATES					
1	1	(\$0.983)	GAS GENERATOR	LOX/RP-1	RP-1
2	4	(\$0.484)	GAS GENERATOR	LOX/RP-1	LH2
3	2	(\$0.359)	GAS GENERATOR	LOX/C3H8	C3H8
4	5	\$0.295	GAS GENERATOR	LOX/C3H8	LH2
5	3	\$0.568	GAS GENERATOR	LOX/CH4	CH4
6	6	\$1.111	GAS GENERATOR	LOX/CH4	LH2
2000 ENGINE CANDIDATES					
1	11	(\$1.235)	GAS GENERATOR	LOX/RP-1	LO2
2	12	(\$0.442)	GAS GENERATOR	LOX/C3H8	LO2
3	18	(\$0.060)	GAS GENERATOR	LOX/RP-1/LH2	LH2

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TASK 2 - EVALUATION OF CANDIDATE STBE CONFIGURATIONS

THE OBJECTIVES OF TASK 2 ARE DESCRIBED ON THIS CHART. MOST OF THE EFFORT WILL BE DIRECTED TOWARD IN-DEPTH STUDIES OF THE THREE MAJOR SUBSYSTEMS LISTED TO DEFINE THE OPTIMUM SUBSYSTEM FOR EACH CANDIDATE ENGINE. SUPPORTING STUDIES, AS REQUIRED, WILL BE CONDUCTED TO PROVIDE A BASIS FOR SELECTION OF THE OPTIMUM SUBSYSTEM.

TASK 2 — EVALUATION OF CANDIDATE STBE CONFIGURATIONS

- OBJECTIVES
  - CONDUCT SYSTEM AND SUBSYSTEM TRADE STUDIES TO DEFINE FEATURES WHICH OPTIMIZE THE SELECTED CANDIDATE ENGINES
    - THRUST CHAMBER ASSEMBLY
    - TURBOMACHINERY
    - CONTROL AND HEALTH MONITORING SYSTEM
  - CONDUCT SUPPORTING STUDIES TO PROVIDE BASIS FOR SELECTION
    - LCC
    - RISK
    - HAZARDS
    - FMEA
    - FACILITIES
    - VEHICLE COMPATIBILITY
    - OPERATIONAL FLEXIBILITY
    - TECHNOLOGY STATUS

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TASK 2 - EVALUATION OF CANDIDATE STBE CONFIGURATIONS FLOW DIAGRAM

THIS CHART PRESENTS THE FLOW DIAGRAM FOR THE TASK 2 EFFORT.

THE 9 ENGINE CONFIGURATIONS FOR IN-DEPTH STUDY WERE DEFINED IN TASK 1. BASELINE ENGINE PARAMETERS IN TASK 1 WERE BASED ON 750K LBS THRUST, AND FIXED ORIFICE CONTROLS. THROTTLING WAS NOT CONSIDERED. THE VEHICLE TRADE FACTORS WERE DEVELOPED BY ROCKETDYNE IN ORDER TO MEET THE SCHEDULE.

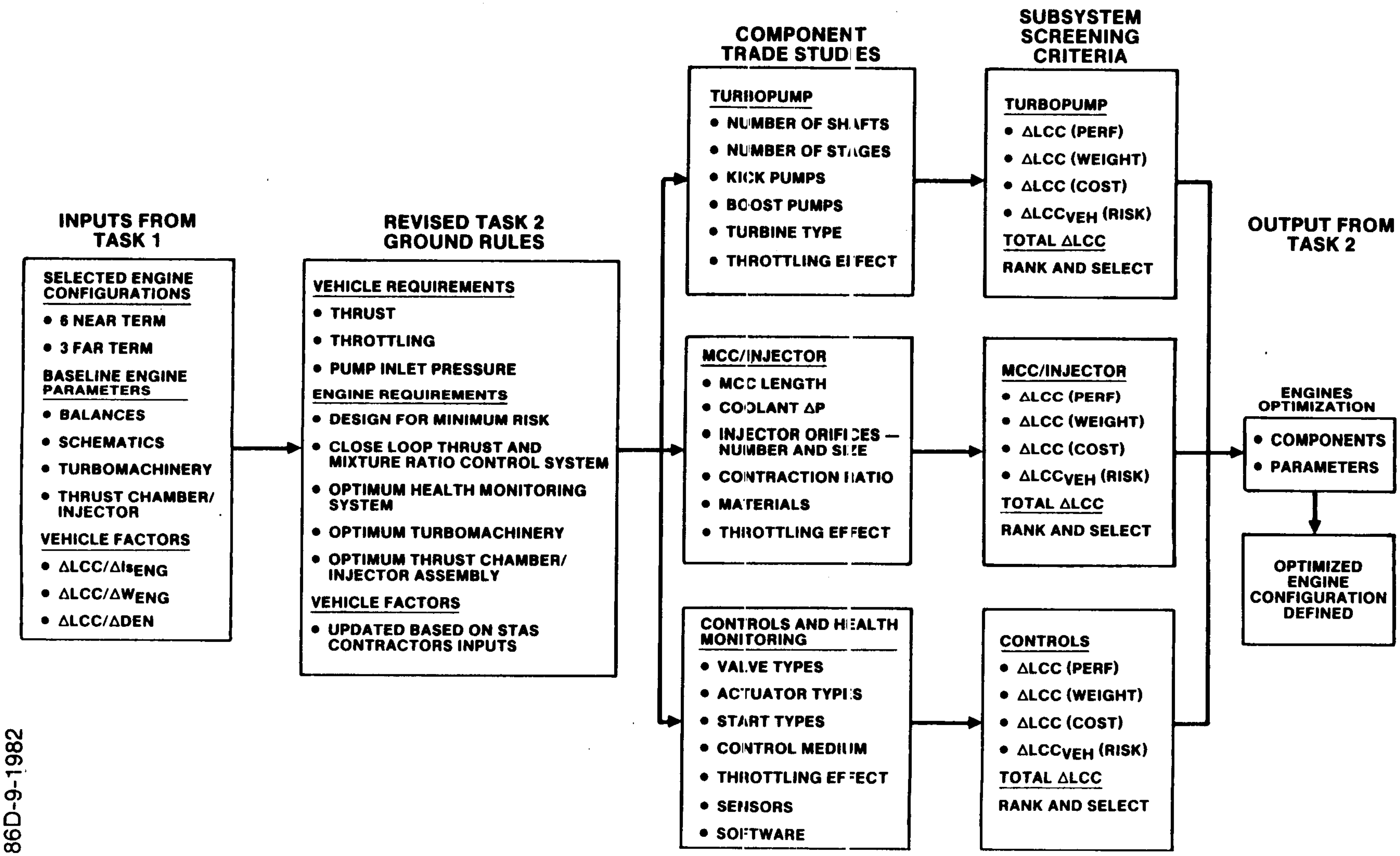
IN TASK 2 THE ENGINE BALANCES WILL BE RE-RUN BASED ON REVISED GROUND RULES WHICH CONSIDER THE ACTUAL VEHICLE AND ENGINE REQUIREMENTS RELATIVE TO THRUST AND THROTTLING.

IN-DEPTH COMPONENT TRADE STUDIES WILL BE CONDUCTED IN THE AREAS OF TURBOMACHINERY, COMBUSTION DEVICES, AND CONTROLS AND HEALTH MONITORING.

SUBSYSTEM SCREENING WILL UTILIZE UPDATED VEHICLE FACTORS BASED ON STAS CONTRACTORS INPUTS.

NEW BALANCES WILL BE RUN FOR THE 9 ENGINE CONFIGURATIONS AFTER THE OPTIMUM SUBSYSTEMS ARE DEFINED.

TASK 2 — EVALUATION OF CANDIDATE STBE CONFIGURATIONS FLOW DIAGRAM



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EVALUATION OF CANDIDATE STBE CONFIGURATIONS APPROACH

THE OVERALL APPROACH TO TASK 2 IS A PARALLEL EFFORT. FIXED DESIGN POINT BALANCES ARE USED TO CONDUCT SUBSYSTEM TRADE STUDIES FOR THE TURBOMACHINERY AND COMBUSTION DEVICES. IN PARALLEL A THROTTLING CONFIGURATION IS DEVELOPED FOR EACH ENGINE AND A BALANCE GENERATED AT THE 750K LB THRUST POINT. AN OFFDESIGN MODEL IS THEN UTILIZED TO PREDICT PERFORMANCE AT 625K LB THRUST. THE CONTROL SYSTEM WILL THEN BE SCOPED FROM THE BALANCE DATA AND A VALVE SENSITIVITY STUDY.

THE TURBOMACHINERY AND COMBUSTION DEVICES WILL THEN BE RE-EVALUATED AGAINST THE THROTTLING CONFIGURATIONS, WITH ADJUSTMENTS MADE AS REQUIRED. FINAL OPTIMIZED BALANCES WILL THEN BE RUN FOR EACH (THROTTLING) CONFIGURATION ENGINE. THE DATA WILL BE USED TO SELECT THE BEST 1996 AND 2000 ENGINE CANDIDATE USING THE APPROVED EVALUATION AND SELECTION CRITERIA PLAN.

STBE SYSTEMS ANALYSES APPROACH

PARALLEL EFFORT

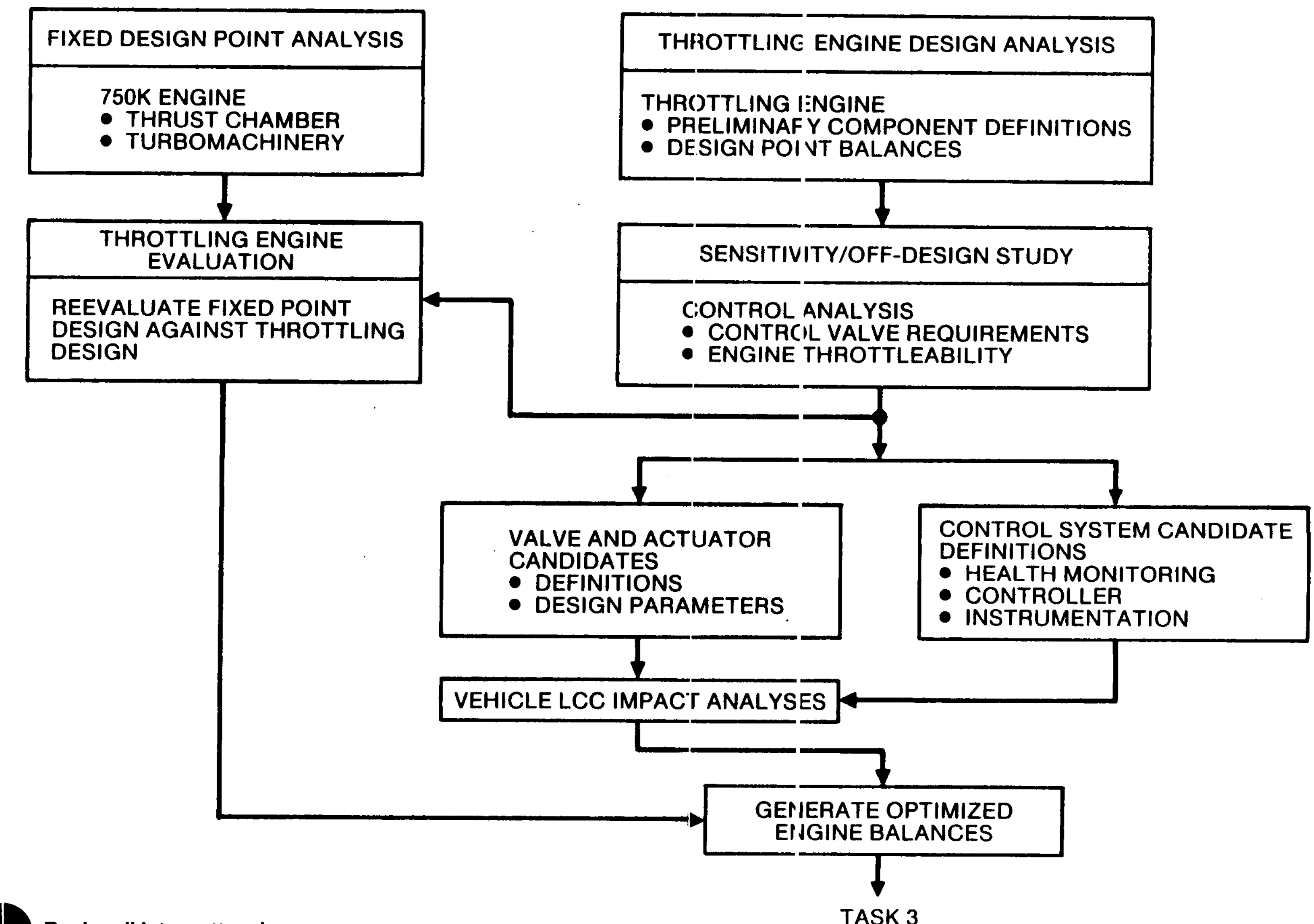
- **CONDUCT SUBSYSTEM TRADE STUDIES USING 750 klb THRUST FIXED DESIGN POINT ENGINE BALANCES AS BASELINE**
  - TURBOMACHINERY
  - COMBUSTION DEVICES
- **DEVELOP THROTTLING CONFIGURATION FOR EACH ENGINE CANDIDATE**
  - GENERATE ENGINE BALANCES FOR THE THROTTLING CONFIGURATIONS AT 750 klb THRUST OPERATING POINT
  - USE OFF-DESIGN COMPUTER MODEL TO PREDICT ENGINE PERFORMANCE AT 625 klb THRUST OPERATING POINT
  - DEFINE CONTROL SYSTEM REQUIREMENTS BASED ON ENGINE BALANCES AND VALVE SENSITIVITY STUDY
- **REEVALUATE SELECTED SUBSYSTEMS FOR THROTTLING CONFIGURATION**
- **GENERATE NEW ENGINE BALANCES FOR THE OPTIMIZED THROTTLING CONFIGURATION ENGINES**

86D-9-1980

TASK 2 - SYSTEM ANALYSES FLOW DIAGRAM

THIS FLOW DIAGRAM SHOWS HOW THE FIXED POINT DESIGN COMPONENT STUDIES WILL BE RE-EVALUATED WITH THE THROTTLING ENGINE BALANCES TO FINALIZE THE COMPONENT CONFIGURATIONS PRIOR TO GENERATING OPTIMIZED BALANCES.

TASK 2 — SYSTEM ANALYSES FLOW DIAGRAM



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LH_2 COOLED ENGINE GROUNDRULE CHANGES

THESE ARE THE CHANGES FROM THE TASK 1 GROUNDRULES INCORPORATED INTO THE FIXED DESIGN POINT BALANCES. THEY AFFECT THE HYDROGEN COOLED ENGINES ONLY.

LH_2 COOLED ENGINE GROUNDRULE CHANGES

PARAMETER/COMPONENT	CHANGE	REASON	EFFECT
UPPER P_c LIMIT	CHANGED TO LH_2 PUMP TIP SPEED LIMIT	IMPROVED PERFORMANCE	INCREASED P_c
LH_2 PUMP STAGES	NEAR-TERM LIMIT INCREASED TO 3	CONSISTENCY WITH SSME	INCREASED P_c FOR NEAR-TERM
PUMP STAGE HEAD COEFFICIENT	UPPER LIMIT OF 0.55 ADDED	THROTTLEABLITY AND DESIGN MARGIN	DECREASED P_c
HYDROSTATIC BEARINGS	ELIMINATED AS NEAR-TERM CANDIDATE	DEVELOPMENT TIME	FOR NEAR-TERM, INCREASED LH_2 $\dot{w}$ AND LH_2 TURBO-PUMP WEIGHT

NET IMPACT OF GROUND RULE CHANGES

- **P_c INCREASED 35–60%**
- **Isp INCREASED 4–6 SECONDS**

86C-9-677

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STBE FIXED POINT DESIGN CHARACTERISTICS
(1995 ENGINES)

THIS CHART SUMMARIZES THE FIXED POINT BALANCE DATA FOR THE 1995 IOC ENGINES.

STBE FIXED POINT DESIGN CHARACTERISTICS
(1995 ENGINES)

CATEGORY	FUEL-COOLED			LH2-COOLED		
ENGINE NUMBER	1	2	3	4	5	6
THRUST (klb)	750	750	750	750	750	750
CYCLE	GG	GG	GG	GG	GG	GG
PROPELLANTS	LOX/RP-1	LOX/C3H8	LOX/CH4	LOX/RP-1	LOX/C3H8	LOX/CH4
COOLANT	RP-1	C3H8	CH4	LH2	LH2	LH2
TURBINE DRIVE GAS	LOX/RP-1	LOX/C3H8	LOX/CH4	LOX/LH2	LOX/LH2	LOX/LH2
TURBINE GAS TYPE	F.R.	F.R.	F.R.	F.R.	F.R.	F.R.
CHAMBER PRES (psia)	2350	3407	3495	4165	4170	4200
SPECIFIC IMPULSE (s)						
VACUUM	329.2	344.7	350.0	348.6	357.4	361.4
SEA LEVEL	284.6	302.6	308.1	309.0	316.7	320.8
LOX PUMP Pd (psia)	2996	4344	4456	5310	5317	5355
FUEL PUMP Pd (psia)	3476/6943	4770/6306	4866/6195	5477	5484	5523
LH_2 PUMP Pd (psia)	DNA	DNA	DNA	6575	6584	6640
WEIGHT (lb)	7669	7794	8074	7719	7715	7957
LENGTH (in.)	163	152	150	147	147	146
DIAMETER (in.)	101	95	94	91	91	91
NOZZLE ε	42.9	56.9	57.1	64.3	64.9	64.6

F.R. = FUEL RICH

86D-9-1984

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STBE FIXED POINT DESIGN CHARACTERISTICS
(2000 ENGINES)

THIS CHART SUMMARIZES THE FIXED POINT BALANCE DATA FOR THE 2000 IOC ENGINES.

STBE FIXED POINT DESIGN CHARACTERISTICS
(2000 ENGINES)

CATEGORY	LOX-COOLED		LH2-COOLED
ENGINE NUMBER	11	12	18
THRUST (klb)	750	750	750
CYCLE	GG	GG	GG
PROPELLANTS	LOX/RP-1	LOX/C3H8	LOX/RP-1/LH2
COOLANT	LOX	LOX	LH2
TURBINE DRIVE GAS	LOX/RP-1	LOX/C3H8	LOX/LH2
TURBINE GAS TYPE	F.R.	F.R.	F.R.
CHAMBER PRES (psia)	3380	3850	5760
SPECIFIC IMPULSE (s)			
VACUUM	343.1	350.2	366.2
SEA LEVEL	301.1	308.8	328.4
LOX PUMP Pd (psia)	4503/6210	5170/7476	7344
FUEL PUMP Pd (psia)	4449	5068	7574
LH_2 PUMP Pd (psia)	DNA	DNA	9745
WEIGHT (lb)	7528	8002	8388
LENGTH (in.)	152	149	137
DIAMETER (in.)	95	93	86
NOZZLE ε	56.7	62.8	82.2
F.R. = FUEL RICH			

86D-9-1983

STBE CONFIGURATION STUDY
SECOND QUARTERLY REVIEW
AGENDA

- INTRODUCTION .... F. KIRBY
- TASK 1 SUMMARY .... A. WEISS
- TASK 2 STATUS REVIEW
  - SUBSYSTEM OPTIMIZATION APPROACH .... A. WEISS
  - TURBOMACHINERY STUDIES .... A. EASTLAND
  - COMBUSTION DEVICES STUDIES .... P. MEHEGAN
  - THROTTLING ON-DESIGN/OFF-DESIGN STUDY .... W. BISSELL, D. NGUYEN
  - CONTROL SYSTEM AND HEALTH MONITOR STUDIES .... R. BREWSTER
- SUMMARY .... A. WEISS

86C-9-681-4

TURBOMACHINERY AGENDA

THIS IS THE AGENDA FOR THE TURBOMACHINERY SECTION OF THIS PRESENTATION

TURBOMACHINERY AGENDA

- INTRODUCTION
- APPROACH LOGIC
- REQUIREMENTS
- GROUND RULES
- TURBOMACHINERY CANDIDATES
- FINAL SELECTION APPROACH

STBE TURBOMACHINERY STUDIES

THE OBJECTIVE OF THE TURBOMACHINERY STUDY IS TO SELECT THE TURBOPUMPS THAT CREATE THE OPTIMUM TURBOMACHINERY SYSTEM FOR EACH OF THE NINE ENGINES SELECTED IN TASK I.

TO ACHIEVE THIS, VIABLE TURBOMACHINERY SYSTEMS WERE CONSIDERED FOR EACH ENGINE, THE MOST PROMISING OF THESE WERE IDENTIFIED THROUGH AN ENGINEERING SCREENING PROCESS AND RECOMMENDED FOR LIFE CYCLE COST ANALYSIS, WHERE THE OPTIMUM SYSTEM FOR EACH ENGINE WILL BE SELECTED.

CURRENTLY, THE ENGINEERING SCREENING PROCESS IS COMPLETE FOR FOUR OF THE NINE ENGINES, WITH THE OTHER FIVE IN WORK. THESE ENGINES ARE ENGINE 1 (LOX/RP-1, RP-1 COOLED), ENGINE 3 (LOX/METHANE, METHANE COOLED), ENGINE 4 (LOX/RP-1, HYDROGEN COOLED), AND ENGINE 6 (LOX/METHANE, HYDROGEN COOLED), AND ARE ALL CURRENT TECHNOLOGY ENGINES.

STBE TURBOMACHINERY STUDIES

- **OBJECTIVE**
  - SELECT OPTIMUM TURBOMACHINERY FOR THE NINE CANDIDATE ENGINES
- **APPROACH**
  - IDENTIFY CANDIDATE TURBOMACHINERY SYSTEMS FOR EACH ENGINE
  - RECOMMEND PROMISING SYSTEMS THROUGH ENGINEERING SCREENING PROCESS
  - SELECT OPTIMUM CONFIGURATION FOR EACH ENGINE THROUGH LIFE CYCLE COST ANALYSIS
- **STATUS**
  - SCREENING COMPLETE FOR FOUR ENGINES (1, 3, 4, 6)

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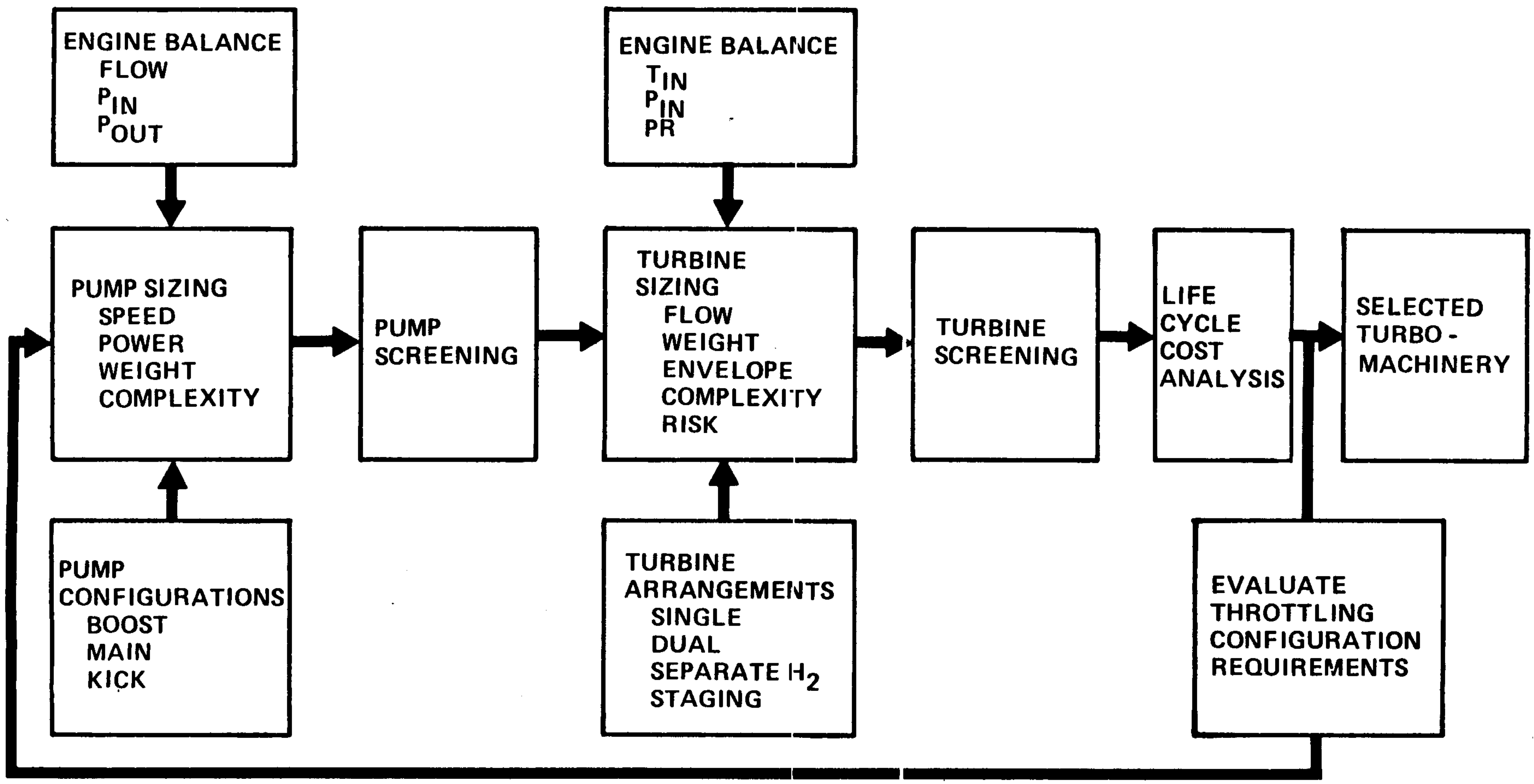
TURBOMACHINERY SELECTION APPROACH

PUMP (OR HYDRAULIC FLOW CIRCUIT) CONFIGURATIONS CONSISTING OF COMBINATIONS OF BOOST (OR LOW PRESSURE) PUMPS, MAIN PUMPS AND KICK PUMPS ARE SIZED WITHIN THE SPECIFIED GROUNDRULES TO SATISFY THE ENGINE BALANCE REQUIREMENT OF DELIVERED FLOW, AND INLET AND DISCHARGE PRESSURE. COMPUTER PROGRAMS DEVELOPED DURING IN-HOUSE STUDIES ALLOW DESIGN PARAMETERS TO BE VARIED OVER A WIDE RANGE TO ENSURE COMPONENT OPTIMIZATION. THESE PUMP CONFIGURATIONS ARE SCREENED ON THE BASIS OF MAIN PUMP SPEED (HIGH SPEED GIVING SMALLER TURBINE DIAMETER, LARGER TURBINE BLADE HEIGHT-REDUCING THE LIKELIHOOD OF PARTIAL ADMISSION, AND LOWER MAIN PUMP WEIGHT), POWER (LOWER REQUIRED POWER REDUCING TURBINE FLOWRATE AND INCREASING ENGINE SPECIFIC IMPULSE), WEIGHT AND COMPLEXITY. PROMISING CONFIGURATIONS ARE CARRIED FORWARD FOR SIZING OF THE TURBINE (OR HOT GAS CIRCUIT) CONFIGURATION. IN THIS PHASE TURBINES ARE SIZED WITHIN THE SPECIFIED GROUNDRULES TO DRIVE THE RECOMMENDED PUMP CONFIGURATIONS USING VALUES OF INLET PRESSURE AND OVERALL PRESSURE RATIO TAKEN FROM THE ENGINE BALANCES. SINGLE SHAFT TURBINE ARRANGEMENTS (FUEL AND OXIDIZER PUMPS DRIVEN BY A SINGLE TURBINE), DUAL SHAFT TURBINE ARRANGEMENTS (FUEL AND OXIZIDER PUMPS DRIVEN BY SEPARATE TURBINES) AND TURBINES FOR THE HYDROGEN PUMPS, WHERE REQUIRED, ARE ALL CONSIDERED IN THIS PHASE, USING COMBINATIONS OF IMPULSE AND REACTION TURBINE STAGES. ROCKETDYNE'S GASPATH COMPUTER PROGRAM, WHICH IS A PROVEN TURBINE DESIGN TOOL, WAS USED FOR THIS PHASE. AFTER A FURTHER SCREENING PROCESS, BASED ON TURBINE FLOWRATE, SYSTEM WEIGHT, SYSTEM ENVELOPE AND SYSTEM COMPLEXITY, A LIFE CYCLE COST ANALYSIS SELECTS THE OPTIMUM TURBOMACHINERY CONFIGURATION FOR EACH ENGINE. THE OFF DESIGN PERFORMANCE OF THE SELECTED CONFIGURATION IS CHECKED TO ENSURE ACCEPTABLE EFFICIENCY AND MARGINS AT BOTH 750K THRUST AND 625K THRUST, AND IF NECESSARY THE PROCESS IS REPEATED.

TURBOMACHINERY SELECTION APPROACH



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TURBOMACHINERY REQUIREMENTS FOR SELECTED ENGINES

THIS TABLE LISTS THE TURBOMACHINERY REQUIREMENTS (PUMP FLOWRATES, INLET PRESSURES AND DISCHARGE PRESSURES, TURBINE INLET PRESSURES AND OVERALL PRESSURE RATIOS) AS SET BY THE NINE ENGINE CYCLES UNDER CONSIDERATION.

TURBOMACHINERY REQUIREMENTS FOR SELECTED ENGINES

ENGINE NO.	FUEL	COOLANT	PUMP	FLOWRATE, GPM @ 750K	ENGINE INLET PRESSURE, PSI	PUMP DISCHARGE PRESSURE, PSI	TURBINE INLET PRESSURE PSI	OVERALL PRESSURE RATIO
1	RP-1	RP-1	LOX RP-1	11797 6857	65 45	2996 3475, 6943*	2338	20
2	C_3H_8	C_3H_8	LOX C_3H_8	11351 6680	65 45	4344 4470, 6305*	3390	20
3	CH_4	CH_4	LOX CH_4	11514 10320	65 45	4456 4865, 6195*	3477	20
4	RP-1	LH_2	LOX LH_2 RP-1	11139 3179 5644	65 25 45	5310 6574 5477	4144	20
5	C_3H_8	LH_2	LOX LH_2 C_3H_8	11146 3232 5597	65 25 45	5316 6583 5483	4144	20
6	CH_4	LH_2	LOX LH_2 CH_4	11296 3910 8629	65 25 45	5355 6640 5523	4179	20
11	RP-1	LOX	LOX RP-1	11183 6438	65 45	4503 4448, 6210*	3350	20
12	C_3H_8	LOX	LOX C_3H_8	11188 6441	65 45	5710 5068, 7476*	3835	20
18	RP-1	LH_2	LOX LH_2 RP-1	10873 4101 5214	65 25 45	5100 6267 5260	3905	20

*TWO DELIVERY PRESSURES REQUIRED FOR THE TWO COOLANT CIRCUITS (NOZZLE AND JACKET)

86C-9-536

PHILOSOPHY FOR COMPONENT SIZING

TO REDUCE THE SIZE OF THE CONFIGURATION MATRIX WHILE ENSURING THAT EVERY FAVORABLE SYSTEM WAS CONSIDERED, THE KNOWLEDGE GAINED FROM IN-HOUSE STUDIES WAS USED TO ESTABLISH THE CANDIDATE SYSTEMS.

TYPICAL DUCT LOSSES BETWEEN TURBOMACHINERY COMPONENTS (INCLUDING VOLUTE AND BABYPANTS INLET LOSSES) WERE INCLUDED TO ENSURE ACCURATE MODELING OF THE SYSTEMS.

GROUNDRULES FOR THE HYDRODYNAMIC AND AERODYNAMIC DESIGN PARAMETERS WERE SET TO ENSURE EFFICIENT COMPONENT OPERATION FOR THE SPECIFIED 100 MISSION LIFE.

GROUNDRULES IMPOSED BY STRUCTURAL AND MECHANICAL LIMITS WERE SET ACCORDING TO THE SPECIFIED TECHNOLOGY LEVELS. THE 1990 TECHNOLOGY LEVEL LIMITS REPRESENT ROCKETDYNE'S BEST ESTIMATE OF WHAT THE TECHNOLOGY ADVANCES WILL BE IF A REASONABLE EFFORT IS MADE TO ACHIEVE THOSE ADVANCES.

SIGNIFICANT SIZE, WEIGHT AND PERFORMANCE PENALTIES ARE INCURRED WHEN THE HYDROGEN PUMP SPEED IS REDUCED TO THAT OF THE FUEL OR LOX PUMP.

PHILOSOPHY FOR COMPONENT SIZING

- RESULTS FROM IN-HOUSE STUDIES USED TO ESTABLISH PRIMARY CANDIDATES
- TYPICAL TURBOMACHINERY DUCTING LOSSES INCLUDED
- HYDRODYNAMIC AND AERODYNAMIC DESIGN PARAMETERS (ϕ, ψ, u/C_O, ETC) SET WITHIN DEMONSTRATED LIMITS
- STRUCTURAL/MECHANICAL LIMITS SET BY SPECIFIED TECHNOLOGY LEVELS
- LH_2 TURBOPUMPS ALWAYS ON SEPARATE SHAFT DUE TO HIGH SPEED

HYDRAULIC FLOW CIRCUIT CONFIGURATIONS

THE FOUR HYDRAULIC FLOW CIRCUITS THAT WERE CONSIDERED ARE: MAIN PUMP ONLY, MAIN PUMP + KICK PUMP, BOOST PUMP + MAIN PUMP, AND BOOST PUMP + MAIN PUMP + KICK PUMP

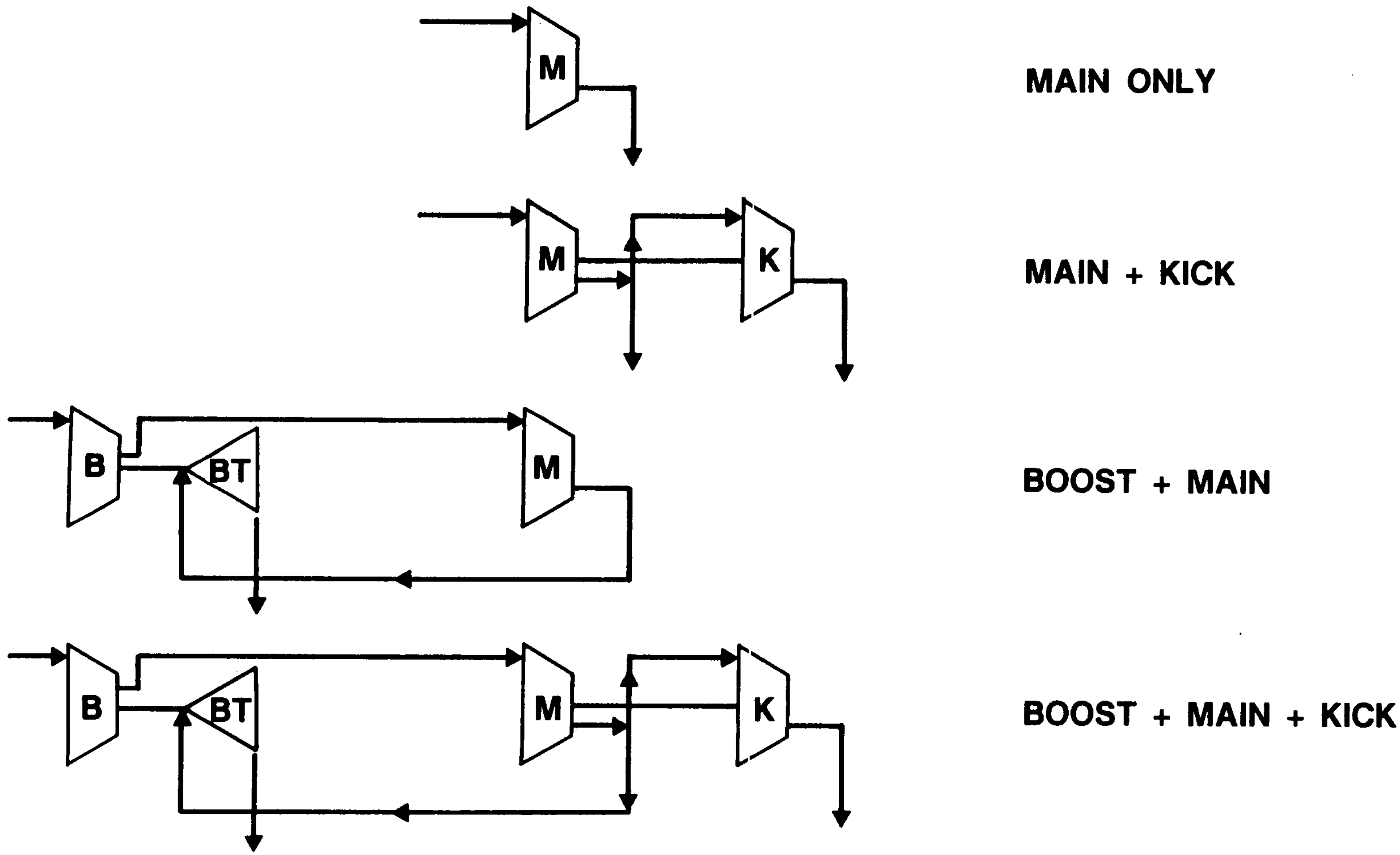
A MAIN PUMP ONLY REPRESENTS THE SIMPLEST CONFIGURATION.

FOR PROPELLANT COOLED CYCLES, TWO DELIVERY PRESSURES ARE REQUIRED FOR THE COOLANT - A LOWER PRESSURE FOR THE NOZZLE COOLANT CIRCUIT AND A HIGHER PRESSURE FOR THE THRUST CHAMBER JACKET COOLANT CIRCUIT. A CONFIGURATION WITH A MAIN PUMP AND A KICK PUMP ON A SINGLE SHAFT, IN WHICH ONLY THE FLOW REQUIRED BY THE THRUST CHAMBER JACKET COOLANT CIRCUIT IS PUMPED TO THE HIGHER PRESSURE BY THE KICK PUMP, GENERALLY REQUIRES THE MINIMUM POWER.

BOOST PUMPS CAN BE ADDED UPSTREAM OF EITHER OF THE ABOVE CONFIGURATIONS TO INCREASE THE MAIN PUMP INLET PRESSURE. THIS ALLOWS THE MAIN (AND KICK) PUMP TO RUN AT HIGHER SPEED FOR THE SAME NPSH MARGIN, AND REDUCES WEIGHT AND SIZE.

THE DRIVES FOR THE BOOST PUMPS SHOWN HERE ARE FULL FLOW HYDRAULIC TURBINES, AND ARE DISCUSSED ON THE NEXT CHART.

HYDRAULIC FLOW CIRCUIT CONFIGURATION



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GROUNDRULES FOR PUMP CONFIGURATIONS SIZING

IN-HOUSE STUDIES HAVE SHOWN THAT FULL-FLOW HYDRAULIC TURBINES, IN WHICH ALL OF THE FLOW IS USED TO DRIVE THE BOOST PUMP BEFORE BEING DELIVERED TO THE SYSTEM, HAVE CONSIDERABLE ADVANTAGES OVER RECIRCULATORY FLOW HYDRAULIC TURBINES AND GAS TURBINES. IN THE RECIRCULATORY FLOW SYSTEM, A SMALL FRACTION OF THE FLOW IS TAPPED OFF, USED TO DRIVE THE BOOST PUMP AND THEN RETURNED TO MAIN FLOW AT THE BOOST PUMP DISCHARGE. PREVIOUS STUDIES INDICATED THAT THE BOOST PUMP TURBINES FOR THESE SYSTEMS OPERATED IN AN UNFAVORABLY LOW SPECIFIC SPEED RANGE. GAS TURBINES WERE NOT CONSIDERED FOR THE LOX BOOST PUMP TURBINES DUE TO PURGE SEAL REQUIREMENTS AND WERE LARGE AND OF LOW EFFICIENCY FOR THE FUEL BOOST PUMP DRIVES.

IN THE CONFIGURATION CONTAINING BOOST PUMP, MAIN PUMP AND KICK PUMP THE BOOST PUMP CAN BE DRIVEN BY FLOW FROM THE MAIN PUMP OR KICK PUMP DISCHARGE. THE LATTER WAS NOT CONSIDERED AS PREVIOUS STUDIES HAD SHOWN THAT IT RESULTED IN HIGHER PRESSURES IN THE BOOST PUMP TURBINE AND CONNECTING DUCTS, WITH NO SIGNIFICANT PERFORMANCE ADVANTAGE.

INDUCER ONLY BOOST PUMPS WERE USED TO MINIMIZE THE POWER REQUIRED BY THE BOOST PUMP AND TO REDUCE COMPLEXITY.

INDUCERS WERE USED UPSTREAM OF THE FIRST STAGE OF ALL MAIN PUMPS TO MAXIMIZE MAIN PUMP SUCTION PERFORMANCE, WHICH MAXIMIZES SPEED (AND HENCE MINIMIZES SIZE AND WEIGHT) AND MINIMIZES BOOST PUMP POWER REQUIREMENT.

GROUND RULES FOR PUMP CONFIGURATION SIZING

- **FULL FLOW HYDRAULIC TURBINES USED FOR BOOST PUMP DRIVES**
  - PERFORMANCE ADVANTAGE OVER RECIRCULATORY FLOW HYDRAULIC TURBINES
  - SIZE AND PERFORMANCE ADVANTAGE OVER GAS TURBINES
- **BOOST PUMPS DRIVEN FROM KICK PUMP DISCHARGE NOT INCLUDED**
  - NO PERFORMANCE ADVANTAGE
  - HIGH PRESSURE BOOST PUMP TURBINE AND DUCTING
- **INDUCER ONLY BOOST PUMPS**
  - OPTIMUM PERFORMANCE
  - REDUCED COMPLEXITY
- **INDUCERS UPSTREAM OF THE FIRST STAGE OF ALL MAIN PUMPS**
  - MINIMUM SIZE FOR REQUIRED LIFE

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GROUNDRULES FOR PUMP SIZING

HYDRODYNAMIC DESIGN PARAMETERS

THE RANGE OF VALUES USED FOR THE HYDRODYNAMIC PUMP DESIGN PARAMETERS REFLECTS ROCKETDYNE'S EXPERIENCE IN DESIGNING HIGH PERFORMANCE, LIGHTWEIGHT, RELIABLE TURBOPUMPS FOR LIQUID ROCKET ENGINE APPLICATIONS.

INDUCER NPSH MARGINS AND IMPELLER MAXIMUM OPERATING SUCTION SPECIFIC SPEED WERE SET TO ENSURE NO PUMP HEAD LOSS AND NO MATERIAL EROSION DUE TO CAVITATION.

INDUCER AND IMPELLER FLOW AND HEAD COEFFICIENT RANGES AND THE IMPELLER EYE-TO-TIP DIAMETER RATIO LIMIT REPRESENT VALUES FOR WHICH GOOD EFFICIENCY AND SUCTION PERFORMANCE HAS BEEN DEMONSTRATED.

GROUNDRULES FOR PUMP SIZING
HYDRODYNAMIC DESIGN PARAMETERS

GROUNDRULE	VALUE	RATIONALE
NPSH MARGIN FOR BOOST PUMP OR MAIN PUMP ALONE	20%	DEMONSTRATED VALUES WITH NO LIFE LIMITATION DUE TO CAVITATION
NPSH MARGIN FOR MAIN PUMP FOLLOWING BOOST PUMP	100%	
MAXIMUM SUCTION SPECIFIC SPEED FOR IMPELLER FOLLOWING INDUCER	5000	
INDUCER FLOW COEFFICIENT	0.05 TO 0.3	DEMONSTRATED EFFICIENT OPERATION AND GOOD SUCTION PERFORMANCE
IMPELLER FLOW COEFFICIENT	0.14 TO 0.36	
INDUCER HEAD COEFFICIENT	0.15 TO 0.20	
IMPELLER HEAD COEFFICIENT	0.4 TO 0.5 LOX 0.45 TO 0.55 FUEL, LH_2	
MAXIMUM IMPELLER EYE-TO-TIP DIAMETER RATIO	0.75	LIMIT FOR EFFICIENT IMPELLER OPERATION

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GROUNDRULES FOR PUMP SIZING

STRUCTURAL/MECHANICAL CONSTRAINTS

THE STRUCTURAL AND MECHANICAL CONSTRAINTS WERE SET BY CURRENT TECHNOLOGY LIMITS AND BY ROCKETDYNE'S BEST GUESS AT TECHNOLOGY LIMIT IMPROVEMENTS AVAILABLE IN 1990.

THE IMPELLER TIP SPEED LIMIT IS SET BY VANE STRESSES, EXCEPT IN HYDROGEN WHERE IT IS SET BY THE DISC BURST SPEED.

THE INDUCER TIP SPEED LIMIT IS SET TO ENSURE THAT INDUCER SUCTION PERFORMANCE IS NOT DEGRADED BY BLADE BLOCKAGE EFFECTS.

BEARING SIZE AND D-N LIMITS ARE SET TO ENSURE THE REQUIRED BEARING LIFE.

GROUNDRULES FOR PUMP SIZING
STRUCTURAL/MECHANICAL CONSTRAINTS

GROUNDRULE	TECHNOLOGY LEVELS CURRENT	TECHNOLOGY LEVELS 1990	RATIONALE	EXPERIENCE	IMPROVEMENT
MAXIMUM IMPELLER TIP SPEED,					
FT/SEC – LOX	900	945	STRUCTURAL/ PERFORMANCE	SSME	MATERIAL PROPERTIES
RP-1	1020	1070			
LC_3H_8(SC)	1230	1290			
LCH_4	1490	1565			
LH_2	2000	2100	DISK BURST	SSME	MATERIAL PROPERTIES
MAXIMUM INDUCER TIP SPEED,					
FT/SEC – LOX	500	525	SUCTION PER-FORMANCE/ STRUCTURAL INTEGRITY	SSME	MATERIAL PROPERTIES
RP-1	565	595			
LC_3H_8(SC)	685	715			
LCH_4	830	870			
LH_2	1110	1165			
MINIMUM ROLLING ELEMENT BEARING SIZE, MM	20	20	BEARING WEAR	MARK 48	
MAXIMUM BEARING DN,					
mm RPM, D 30 mm	2×10^6	5×10^6	BEARING WEAR	MARK 29F	HYDROSTATIC ELEMENTS/LOAD SHARING DEVICES
D 30 mm	1.5×10^6	5×10^6		MARK 49	

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HOT GAS FLOW CIRCUIT OPTIONS

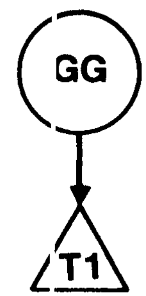
PROPELLANT COOLED ENGINES

FOR THE PROPELLANT COOLED ENGINES, A SINGLE SHAFT CONFIGURATION WAS CONSIDERED, IN WHICH BOTH THE FUEL AND OXIDIZER PUMPS ARE DRIVEN BY THE SAME TURBINE, AND A DUAL SHAFT SERIES CONFIGURATION WAS CONSIDERED IN WHICH THE FUEL AND OXIDIZER PUMPS ARE DRIVEN BY SEPARATE TURBINES IN SERIES. THE DUAL SHAFT PARALLEL CONFIGURATION WILL BE DISCUSSED IN A LATER CHART.

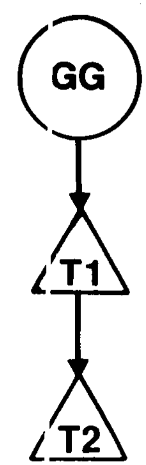
HOT GAS FLOW CIRCUIT OPTIONS
PROPELLANT COOLED ENGINES

SERIES

SINGLE SHAFT



DUAL SHAFT



- NO ADVANTAGE TO PARALLEL TURBINES

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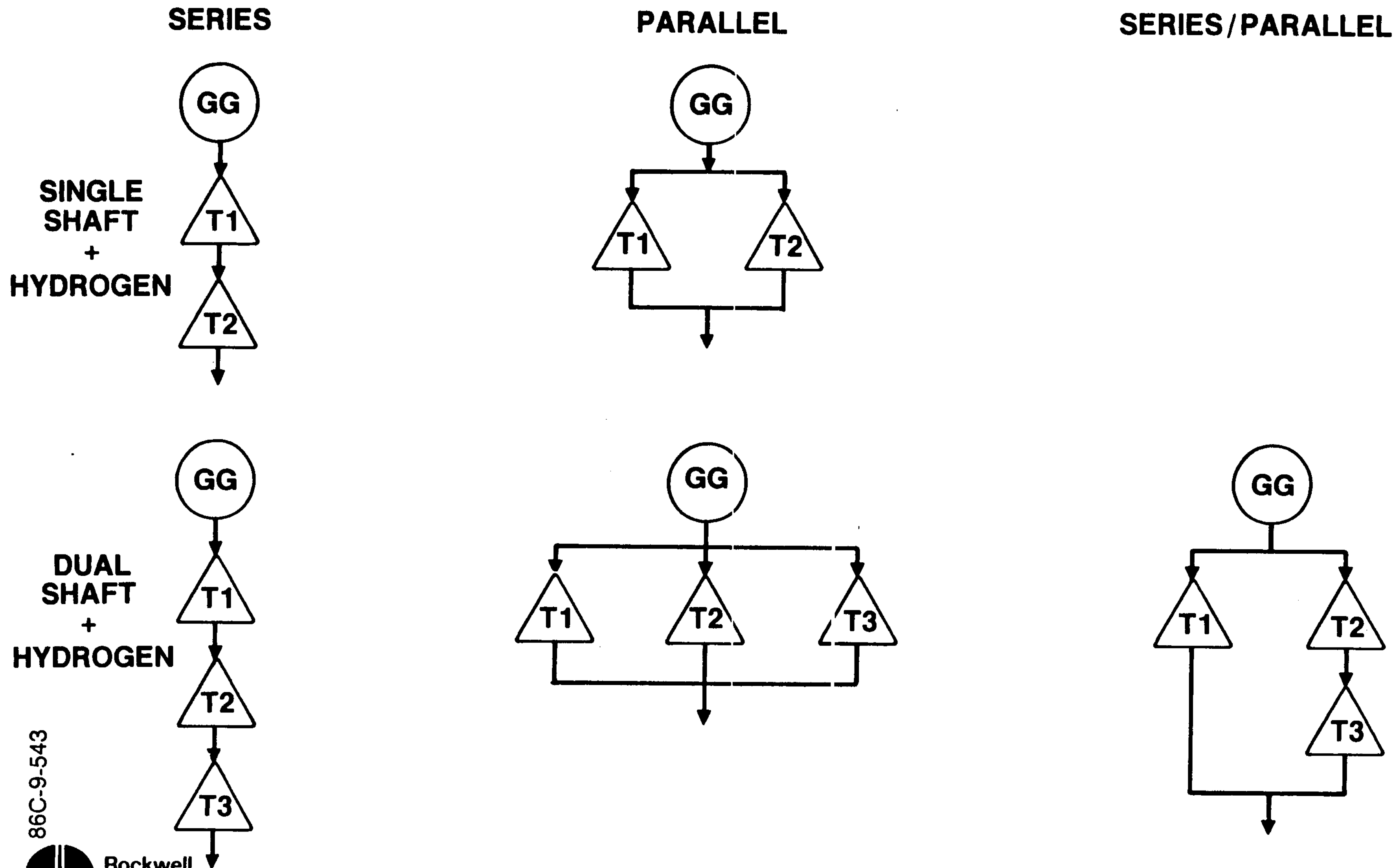
HOT GAS FLOW CIRCUIT OPTIONS

HYDROGEN COOLED ENGINES

THE TURBINE ARRANGEMENTS SHOWN ON THIS CHART WERE ALL CONSIDERED FOR THE HYDROGEN COOLED ENGINES. THE SINGLE SHAFT + HYDROGEN ARRANGEMENTS HAVE A TURBINE DRIVING THE HYDROGEN PUMP AND A SINGLE TURBINE DRIVING BOTH FUEL AND OXIDIZER PUMPS, ARRANGED EITHER IN SERIES OR IN PARALLEL. THE DUAL SHAFT + HYDROGEN ARRANGEMENTS HAVE SEPARATE TURBINES FOR EACH PUMP (TOTAL OF THREE) AND CAN BE ARRANGED IN SERIES, PARALLEL OR A COMBINATION.

HOT GAS FLOW CIRCUIT OPTIONS

HYDROGEN COOLED ENGINES



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GROUNDRULES FOR MAIN TURBINE CONFIGURATION SIZING

IN-HOUSE ENGINE SYSTEM STUDIES INDICATED THAT A SERIES TURBINE ARRANGEMENT REQUIRED CONSIDERABLY LESS FLOW THAN A PARALLEL ARRANGEMENT, AND THUS HAD HIGHER ENGINE SPECIFIC IMPULSE.

IN SERIES ARRANGEMENTS THE TURBINES WERE ARRANGED IN ORDER OF DECREASING SPEED. THIS DECREASES THE TURBINE DIAMETER FOR THE BLADE SPEED REQUIRED FOR THE HIGHEST EFFICIENCY, INCREASING BLADE HEIGHT AND REDUCING THE LIKELIHOOD OF PARTIAL ADMISSION.

GROUNDRULES FOR MAIN TURBINE CONFIGURATION SIZING

- **SERIES TURBINES USED FOR DUAL SHAFT CONFIGURATIONS IN PROPELLANT COOLED ENGINES**
  - SYSTEM STUDY SHOWED IMPROVED PERFORMANCE OVER PARALLEL CONFIGURATION
- **HIGHER SPEED TURBINE PLACED FIRST IN SERIES CONFIGURATIONS**
  - SMALLER DIAMETER FOR GIVEN BLADE SPEED
  - REDUCED LIKELIHOOD OF PARTIAL ADMISSION

GROUNDRULES FOR TURBINE SIZING

AERODYNAMIC DESIGN PARAMETERS

TURBINE AERODYNAMIC PARAMETERS ARE SET TO ENSURE HIGH EFFICIENCY OPERATION AND ARE BASED ON ROCKETDYNE'S EXPERIENCE IN DESIGNING COMPACT, HIGH EFFICIENCY, HIGH POWER DENSITY TURBINES FOR LIQUID ROCKET ENGINE APPLICATIONS.

MINIMIZING WHIRL VELOCITY INCREASES PERFORMANCE AND, IN ADDITION, IF THERE IS A SIGNIFICANT WHIRL VELOCITY COMPONENT AT THE TURBINE EXIT, AN ADDITIONAL BLADE ROW, WITH ASSOCIATED LOSSES AND PENALTIES IN TURBINE SIZE, IS REQUIRED TO REMOVE THE WHIRL.

THE PARTIAL ADMISSION LOSSES AND DYNAMIC BLADE LOADING PROBLEMS OFFSET THE BENEFITS OF OPTIMIZING THE DESIGN U/CO BELOW A MINIMUM ARC OF ADMISSION.

TURBINE STAGING IS CHOSEN SO THAT U/CO IS OPTIMIZED WITHIN THE ABOVE AERODYNAMIC CONSTRAINTS, AND THE STRUCTURAL AND MECHANICAL CONSTRAINTS LISTED LATER.

GROUNDRULES FOR TURBINE SIZING
AERODYNAMIC DESIGN PARAMETERS

GROUNDRULE	VALUE	RATIONALE
TARGET OUTLET FLOW ANGLE	-20 TO 0 DEG (AXIAL)	MINIMIZE EXIT WHIRL
MINIMUM ARC OF ADMISSION	10%	MINIMIZE PARTIAL ADMISSION LOSSES
		REDUCE BLADE LOADING
TARGET U/Co VALUES — 2RVC	0.2 TO 0.25	DEMONSTRATED OPTIMUM EFFICIENCY RANGE
2SPC	0.25 TO 0.3	
1S	0.40	

86C-9-545

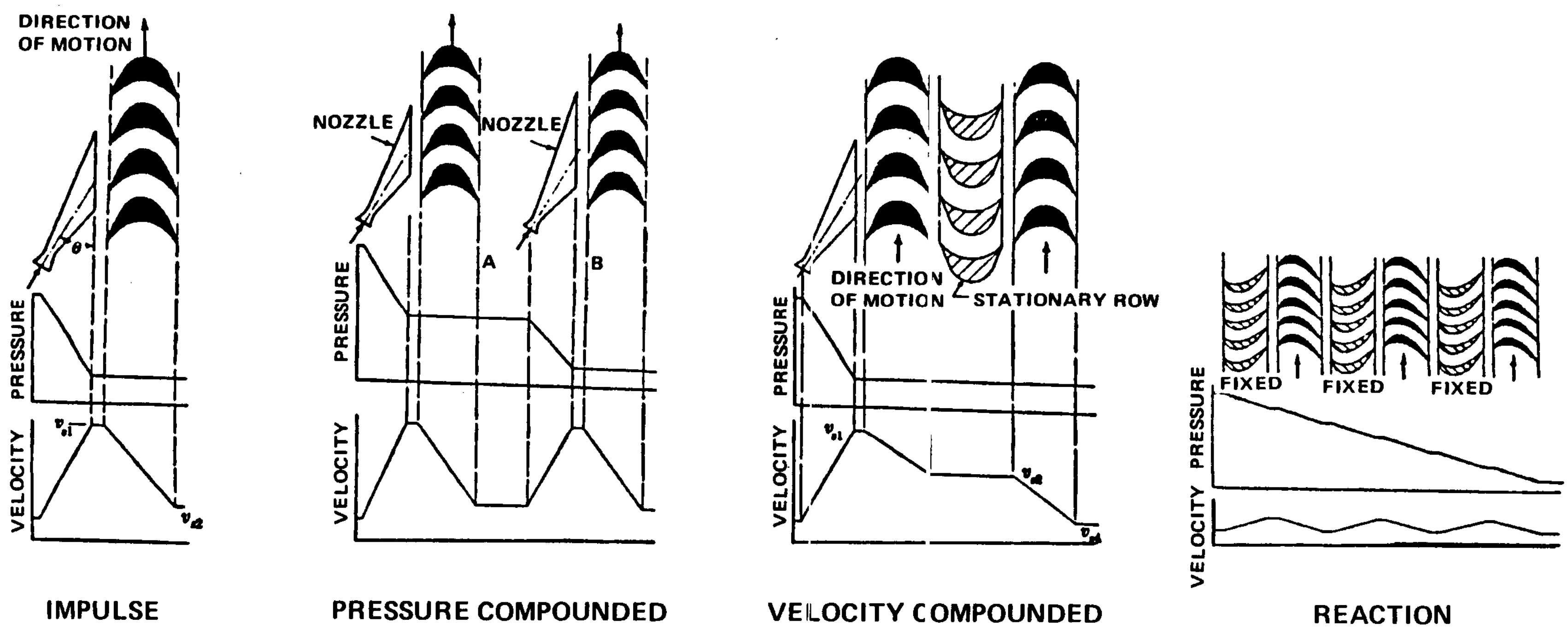
DEFINITION OF TURBINE TYPES

SINGLE STAGE IMPULSE (1S), TWO STAGE PRESSURE COMPOUNDED (2SPC), TWO ROW VELOCITY COMPOUNDED (2RVC) AND TWO STAGE REACTION (2R) STAGING WAS CONSIDERED.

THE FIRST THREE OF THESE USE IMPULSE STAGES, IN WHICH THERE IS NO STATIC PRESSURE DROP ACROSS THE ROTOR. THE FLOW IS ACCELERATED IN THE NOZZLES AND THIS FLUID KINETIC ENERGY CONVERTED TO SHAFT POWER BY THE ROTOR BLADES. IN TWO STAGE PRESSURE COMPOUNDED TURBINES THE FLOW IS REACCELERATED IN A SECOND ROW OF NOZZLES BEFORE THE SECOND ROTOR, WHEREAS IN A TWO STAGE VELOCITY COMPOUNDED TURBINE THE FLOW IS TURNED WITHOUT ACCELERATION IN A STATOR BETWEEN THE TWO ROTORS. IN REACTION STAGES BOTH THE INTERNAL ENERGY OF THE FLUID AND THE KINETIC ENERGY OF THE FLOW IS CONVERTED TO SHAFT POWER IN THE ROTOR. THE STATOR VANES PROVIDE ONLY A SMALL ACCELERATION AND THERE IS A PRESSURE DROP ACROSS THE ROTOR.

REACTION BLADING HAS A HIGHER EFFICIENCY POTENTIAL THAN IMPULSE BLADING, BUT RESULTS IN SIGNIFICANT AXIAL THRUST ON THE ROTOR WHICH MUST BE BALANCED BY THE PUMP.

DEFINITION OF TURBINE TYPES



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GROUNDRULES FOR MAIN TURBINE SIZING

MECHANICAL/STRUCTURAL CONSTRAINTS

THE GROUNDRULES WERE SET BY CURRENT TECHNOLOGY LIMITS AND ALSO BY ROCKETDYNE'S BEST GUESS AT TECHNOLOGY LIMIT IMPROVEMENTS AVAILABLE IN 1990.

THE TEMPERATURE LIMIT IS BASED ON CURRENT SSME PRACTICE AND MATERIAL STRUCTURAL LIMITATIONS. SUCH LIMITATIONS ALSO SET THE BLADE SPEED LIMITS WHICH ARE BASED ON DISK TEMPERATURES BELOW 800 °F. N^2 ANNULUS AREA LIMITS ARE BASED ON UNCOOLED ROTOR BLADES.

GROUNDRULES FOR MAIN TURBINE SIZING
MECHANICAL/STRUCTURAL CONSTRAINTS

GROUNDRULE	TECHNOLOGY LEVEL CURRENT	TECHNOLOGY LEVEL 1990	RATIONALE	EXPERIENCE	IMPROVEMENTS
MAXIMUM INLET TEMPERATURE, DEG R*	2000	2250	FATIGUE LIFE	SSME	MATERIAL PROPERTIES
MAXIMUM MEAN BLADE SPEED, FT/SEC	1650	1750	ULTIMATE STRENGTH	SSME	MATERIAL PROPERTIES
MAXIMUM SPEED SQUARED X ANNULUS AREA $(RPM\text{-}INCH)^2$	8×10^{10}	9.6×10^{10}	ULTIMATE STRENGTH	SSME	MATERIAL PROPERTIES
BLADE HEIGHT TO MEAN DIAMETER RATIO MIN MAX	 .03 .20	 .03 .20	 FABRICATION SKIN FRICTION LOSSES FATIGUE LIFE	 SSME SMALL PUMP PROGRAMS	

*NO TEMPERATURE SPIKES

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ENGINE 1-LOX/RP-1, COOLED

TURBOMACHINERY CANDIDATES

THE NEXT EIGHT CHARTS PRESENT THE RESULTS OF THE ENGINEERING SCREENING FOR ENGINE 1.

TURBOMACHINERY CANDIDATES

ENGINE 1 – LOX/RP-1, RP-1 COOLED

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PUMPS FOR ENGINE 1 - LOX/RP-1, RP-1 COOLED

DUAL SHAFT CONFIGURATIONS

TWO DUAL SHAFT CONFIGURATIONS WERE CARRIED FORWARD FOR TURBINE SIZING AS A RESULT OF THE PUMP SCREENING. THESE WERE THE RP-1 MAIN PUMP + KICK PUMP WITH LOX MAIN PUMP CONFIGURATION (SYSTEM 1A), AND THE RP-1 MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP + MAIN PUMP CONFIGURATION (SYSTEM 1B). THE FORMER HAD THE MINIMUM REQUIRED POWER AND LOWEST COMPLEXITY (SINCE THE RP-1 CONFIGURATION OF MAIN PUMP ALONE REQUIRED TWO STAGES) WHILE THE LATTER HAD THE MAXIMUM SPEED.

THE RP-1 CONFIGURATIONS OF MAIN PUMP ALONE AND BOOST PUMP + MAIN PUMP WERE DELETED. THESE CONFIGURATIONS REQUIRED TWO STAGE MAIN PUMPS DUE TO IMPELLER TIP SPEED AND HEAD COEFFICIENT LIMITS, AND CONFIGURATIONS WITH MAIN PUMP + KICK PUMP OFFERED LOWER POWER REQUIREMENT WITH THE SAME COMPLEXITY.

THE RP-1 CONFIGURATION OF BOOST PUMP + MAIN PUMP + KICK PUMP WAS DELETED AS THE SLIGHT DECREASE IN POWER AND SYSTEM WEIGHT WAS OFFSET BY THE INCREASED COMPLEXITY.

PUMPS FOR ENGINE 1 – LOX/RP-1, RP-1 COOLED
DUAL SHAFT CONFIGURATIONS

SYSTEM IDENTIFIER	RP PUMP CONFIGURATION	LOX PUMP CONFIGURATION	CONCLUSIONS
	MAIN		DELETED • TWO STAGE MAIN PUMP REQUIRED
	BOOST + MAIN		DELETED • TWO STAGE MAIN PUMP REQUIRED
1A	MAIN + KICK	MAIN	CARRIED FORWARD • MINIMUM POWER
1B	MAIN + KICK	BOOST + MAIN	CARRIED FORWARD • MINIMUM DIAMETER
	BOOST + MAIN + KICK		DELETED • PERFORMANCE IMPROVEMENTS INSUFFICIENT TO OFFSET INCREASED COMPLEXITY

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PUMPS FOR ENGINE 1 - LOX/RP-1, RP-1 COOLED

SINGLE SHAFT CONFIGURATIONS

THREE SINGLE SHAFT CONFIGURATIONS WERE CARRIED FORWARD AS A RESULT OF THE PUMP SCREENING. THESE WERE RP-1 MAIN PUMP + KICK PUMP WITH LOX MAIN PUMP (SYSTEM 1C), RP-1 MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP + MAIN PUMP (SYSTEM 1D), AND RP-1 BOOST PUMP + MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP + MAIN PUMP (SYSTEM 1E). SYSTEM 1C HAD THE MINIMUM POWER, MINIMUM WEIGHT AND LOWEST COMPLEXITY, WHILE SYSTEM 1E HAD THE MAXIMUM SHAFT SPEED. SYSTEM 1D REPRESENTED A COMPROMISE, RUNNING AT HIGHER SPEED THAN SYSTEM 1C AND HAVING LOWER COMPLEXITY THAN SYSTEM 1E. THE SYSTEM 1D MAIN PUMP SPEED WAS SET BY THE FUEL PUMP SUCTION PERFORMANCE LIMITS AS OPPOSED TO THE MAJORITY OF SINGLE SHAFT CONFIGURATIONS WHERE IT WAS SET BY THE LOX PUMP SUCTION PERFORMANCE LIMITS. THERE IS LESS NPSH AVAILABLE TO THE FUEL PUMP INDUCER IN SINGLE SHAFT CONFIGURATIONS DUE TO LOSSES INCURRED IN THE VOLUTE OR BABYPANTS TYPE INLET THAT IS REQUIRED WHEN THE FUEL PUMP IS POSITIONED BETWEEN THE LOX PUMP AND THE TURBINE.

CONFIGURATIONS INVOLVING RP-1 MAIN PUMP ONLY AND RP-1 BOOST PUMP + MAIN PUMP WERE DELETED FOR THE REASONS STATED ON THE PREVIOUS CHART.

THE CONFIGURATION WITH RP-1 BOOST PUMP + MAIN PUMP + KICK PUMP WITH LOX MAIN PUMP WAS DELETED AS THE MAIN PUMP SPEED WAS SET BY THE LOX PUMP SUCTION PERFORMANCE, AND THE RP-1 BOOST PUMP SERVES NO PURPOSE.

PUMPS FOR ENGINE 1-LOX/RP-1, RP-1 COOLED
SINGLE SHAFT CONFIGURATIONS

SYSTEM IDENTIFIER	RP PUMP CONFIGURATION	LOX PUMP CONFIGURATION	CONCLUSIONS
	MAIN		DELETED • TWO STAGE MAIN PUMP REQUIRED
	BOOST + MAIN		DELETED • TWO STAGE MAIN PUMP REQUIRED
1C	MAIN + KICK	MAIN	CARRIED FORWARD • MINIMUM POWER, WEIGHT, COMPLEXITY
1D	MAIN + KICK	BOOST + MAIN	CARRIED FORWARD • HIGHER SPEED WITH MEDIUM COMPLEXITY
	BOOST + MAIN + KICK	MAIN	DELETED • NO ADVANTAGE OVER SYSTEM 1A • SPEED CONTROLLED BY LOX PUMP
1E	BOOST + MAIN + KICK	BOOST + MAIN	CARRIED FORWARD • MAXIMUM SPEED

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TURBOMACHINERY FOR ENGINE 1 - LOX/RP-1, RP-1 COOLED

NO FURTHER SYSTEMS WERE DELETED IN THE TURBINE SCREENING PROCESS, AND THUS FIVE SYSTEMS WERE RECOMMENDED FOR LIFE CYCLE COST ANALYSIS.

WITH THE EXCEPTION OF THE LOX TURBINE IN CONFIGURATION 1B, WHICH WAS A TWO STAGE REACTION TURBINE, ALL TURBINES WERE TWO ROW VELOCITY COMPOUNDED, WITH A SMALL DEGREE OF REACTION IN THE SECOND ROTOR. THE REACTION IN THE SECOND ROTOR WAS ADDED TO DECREASE THE MAXIMUM FLUID VELOCITIES THERE AND TO REDUCE THE EXIT WHIRL, BOTH OF WHICH INCREASE THE TURBINE EFFICIENCY.

THE EXPECTED TRENDS IN TURBINE FLOWRATE, SYSTEM WEIGHT, MAXIMUM DIAMETER AND SYSTEM COMPLEXITY ARE OBSERVED:

LOWER TURBINE FLOWRATES FOR THE DUAL SHAFT CONFIGURATIONS WHERE BOTH PUMPS ARE OPTIMIZED (SYSTEMS 1A AND 1B).

LOWER WEIGHTS, LARGER DIAMETERS AND LOWER COMPLEXITIES FOR THE SINGLE SHAFT CONFIGURATIONS (SYSTEMS 1C, 1D, 1E) WHERE FEWER TURBOPUMPS ARE REQUIRED, BUT ONE OF THE PUMPS IS NOT OPTIMIZED.

SMALLER DIAMETERS AND HIGHER COMPLEXITIES FOR THE CONFIGURATIONS WITH BOOST PUMPS (SYSTEMS 1B, 1D, 1E) WHERE THE MAIN PUMP SPEED IS INCREASED BUT ANOTHER TURBOPUMP IS REQUIRED.

SYSTEM 1A HAS THE MINIMUM TURBINE FLOWRATE, SYSTEM 1C THE MINIMUM WEIGHT AND COMPLEXITY, AND SYSTEMS 1B AND 1E THE MINIMUM DIAMETER (SET IN ALL CASES BY THE TURBINE TIP DIAMETER)

IT SHOULD BE NOTED THAT, FOR THIS ENGINE, THE ADDITION OF BOOST PUMPS INCREASES THE SYSTEM WEIGHT, THE WEIGHT OF THE BOOST PUMP OFFSETTING THE REDUCTION IN MAIN PUMP WEIGHT DUE TO THE INCREASED MAIN PUMP SPEED.

TURBOMACHINERY FOR ENGINE 1-LOX/RP-1, RP-1 COOLED
SUMMARY OF CANDIDATES

SYSTEM IDENTIFIER	RP PUMP CONFIG.	LOX PUMP CONFIG.	MAIN TURBOPUMP		SYSTEM WEIGHT LB	MAXIMUM DIAMETER INCH	COMPLEXITY* FACTOR
			ARRANGEMENT	TURBINE FLOWRATE LB/SEC			
1A	MAIN + KICK	MAIN	DUAL	126	1950	24.2	10
1B	MAIN + KICK	BOOST + MAIN	DUAL	129	2076	20.2	13
1C	MAIN + KICK	MAIN	SINGLE	139	1749	28.0	7
1D	MAIN + KICK	BOOST + MAIN	SINGLE	141	1925	26.5	10
1E	BOOST + MAIN + KICK	BOOST + MAIN	SINGLE	138	1836	20.2	13

*COMPLEXITY FACTOR = NUMBER OF SHAFTS (TURBOPUMPS) + NUMBER OF ROTORS (BLADE ROWS) + NUMBER OF PURGE SEALS

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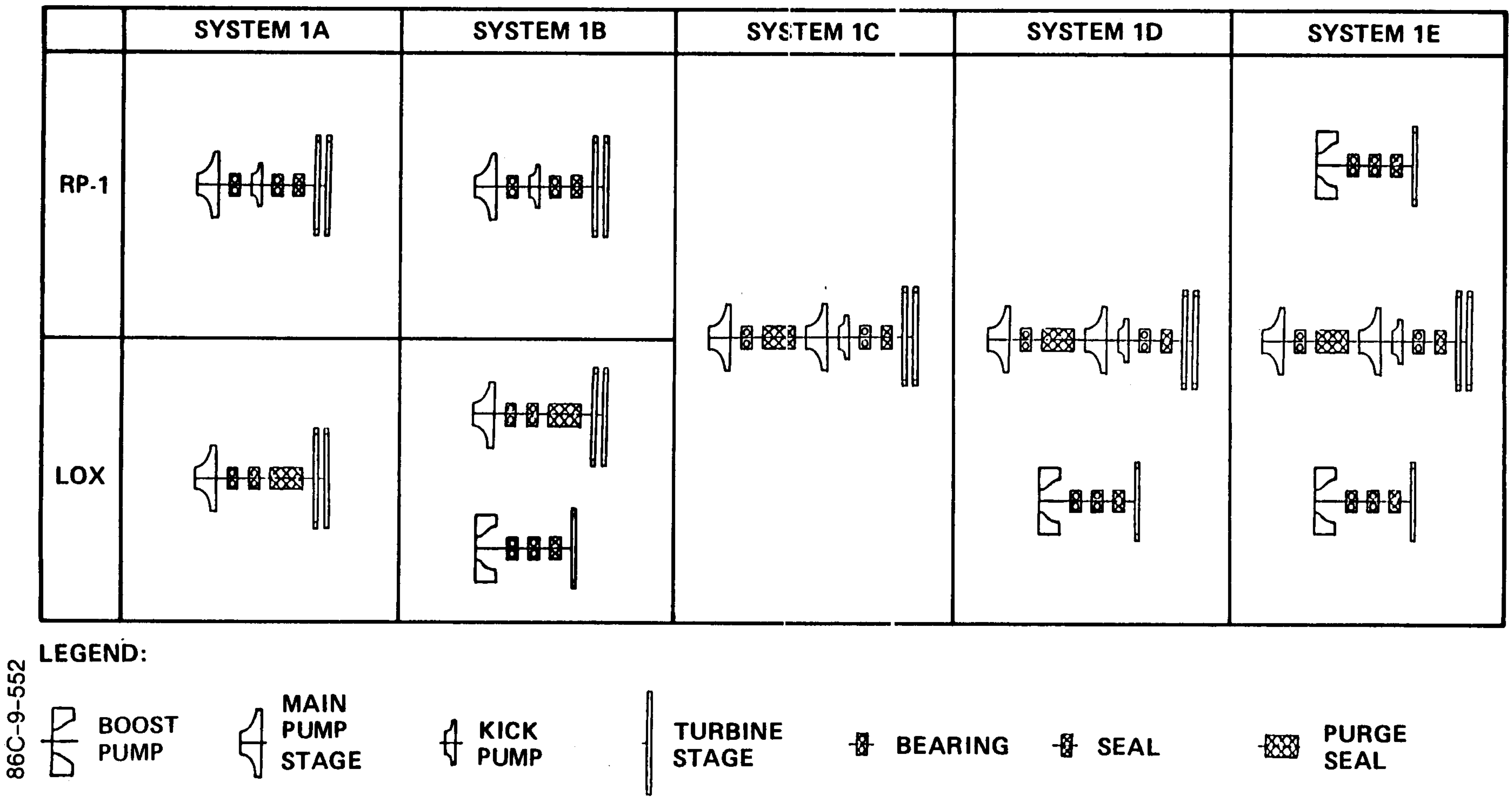
TURBOMACHINERY FOR ENGINE 1-LOX/RP-1, RP-1 COOLED

SCHEMATICS OF CANDIDATES

THESE ARE THE SCHEMATICS OF THE FIVE ENGINE 1 TURBOMACHINERY SYSTEMS RECOMMENDED FOR LIFE CYCLE COST ANALYSIS

TURBOMACHINERY FOR ENGINE 1 – LOX/RP-1, RP-1 COOLED

SCHEMATICS OF CANDIDATES



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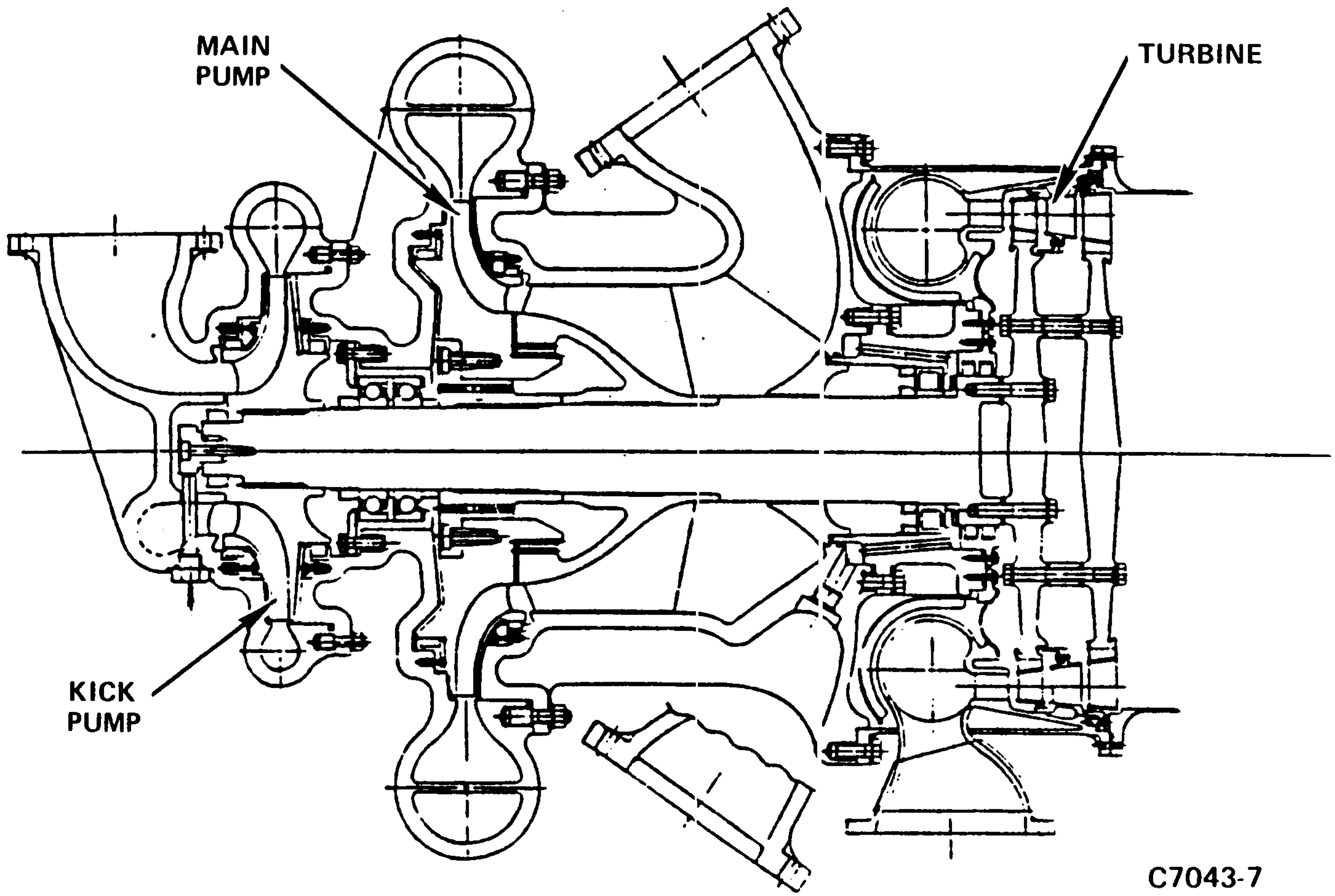
TYPICAL TURBOMACHINERY LAYOUT

THIS IS A TYPICAL TURBOPUMP LAYOUT WITH A MAIN PUMP + KICK PUMP AND TWO STAGE TURBINE. THIS TURBOPUMP WOULD BE SUITABLE FOR USE IN A DUAL SHAFT TURBINE ARRANGEMENT.

TYPICAL TURBOMACHINERY LAYOUT



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TURBOMACHINERY CANDIDATES FOR ENGINE 1

- LOX/RP-1, RP-1 COOLED

SUMMARY OF PUMP DATA

DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE CANDIDATE PUMPS FOR ENGINE 1. PUMP ROTATIONAL SPEEDS WERE ALL SET BY SUCTION PERFORMANCE LIMITS.

TURBOMACHINERY CANDIDATES FOR ENGINE 1
LOX/RP-1, RP-1 COOLED
SUMMARY OF PUMP DATA

SYSTEM		1A	1B	1C	1D	1E
RP-1 PUMP CONFIGURATION		M+K	M+K	M+K	M+K	B+M+K
LOX PUMP CONFIGURATION		M	B+M	M	B+M	B+M
TURBINE ARRANGEMENT		DUAL	DUAL	SINGLE	SINGLE	SINGLE
RP-1 MAIN KICK PUMP	SPEED, RPM	14500	14500	9500	10500	13000
	POWER, HP	27037	27037	31359	30142	28940
	BEARING DN, 10^6 MM RPM	1.08	1.08	0.95	1.03	1.20
	SEAL RUBBING SPEED, FT/SEC	232	232	204	221	258
RP-1 MAIN PUMP	FLOW, GPM	6857	6857	6857	6857	6857
	HEAD, FT	9880	9880	9880	9880	11170
	TIP DIAMETER, INCH	12.6	12.6	19.2	17.4	15.0
	NUMBER OF STAGES	1	1	1	1	1
RP-1 KICK PUMP	FLOW, GPM	3429	3429	3429	3429	3429
	HEAD, FT	10312	10312	10312	10312	8915
	TIP DIAMETER, INCH	12.9	12.9	19.7	17.8	13.4
LOX MAIN PUMP	SPEED, RPM	9500	13000	9500	10500	13000
	POWER, HP	25568	28087	25568	28317	28087
	FLOW, GPM	11798	11798	11798	11798	11798
	HEAD, FT	5945	6731	5945	6675	6731
	TIP DIAMETER, INCH	15.7	12.2	15.7	15.1	12.2
	NUMBER OF STAGES	1	1	1	1	1
	BEARING DN, 10^6MM RPM	0.78	1.01	–	–	–
	SEAL RUBBING SPEED, FT/SEC	134	173	–	–	–
TOTAL SYSTEM POWER	HP	52605	55124	56927	58459	57027
SYSTEM WEIGHT	LB	1950	2076	1749	1925	1836

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TURBOMACHINERY CANDIDATES FOR ENGINE 1 - LOX/RP-1, RP-1 COOLED

SUMMARY OF TURBINE DATA

TURBINE DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE RECOMMENDED ENGINE 1 TURBOMACHINERY SYSTEMS. FOR THE LOX/RP-1 DRIVE GASES THE BLADE SPEED IS SET TO OPTIMIZE U/CO WITHIN THE CONSTRAINT OF THE OTHER GROUNDRULES.

TURBOMACHINERY CANDIDATES FOR ENGINE 1
LOX/RP-1, RP-1 COOLED
SUMMARY OF TURBINE DATA

SYSTEM		1A	1B	1C	1D	1E
RP-1 PUMP CONFIGURATION		M+K	M+K	M+K	M+K	B+M+K
LOX PUMP CONFIGURATION		M	B+M	M	B+M	B+M
TURBINE ARRANGEMENT		DUAL	DUAL	SINGLE	SINGLE	SINGLE
RP-1 OR SINGLE TURBINE	POWER, HP	27037	27037	56927	58459	57027
	SPEED, RPM	14500	14500	9500	10500	13000
	U/Co	0.250	0.250	0.242	0.250	0.249
	STAGING	2-MIXED*	2-MIXED*	2-MIXED*	2-MIXED*	2-MIXED*
	EFFICIENCY	0.728	0.729	0.734	0.742	0.741
	MEAN BLADE SPEED, FT/SEC	807.	797.	1078.	1111.	1106.
	N^2 AA, 10^{10} RPM^2 $INCH^2$	1.15	1.14	1.49	1.89	2.82
	TIP DIAMETER, INCH	14.12	13.97	28.02	26.50	22.22
	BLADE HEIGHT/MEAN DIAM. – MIN	0.049	0.051	0.030	0.034	0.052
	– MAX	0.107	0.108	0.078	0.093	0.140
	ADMISSION, PERCENT	100	100	100	100	100
	PRESSURE RATIO	4.3	4.1	20.1	20.1	20.1
LOX TURBINE	POWER, HP	25568	28087			
	SPEED, RPM	9500	13000			
	U/Co	0.271	0.301			
	STAGING	2-MIXED*	2-REACTION			
	EFFICIENCY	0.745	0.778			
	MEAN BLADE SPEED, FT/SEC	839	944			
	N^2 AA, 10^{10} RPM^2 $INCH^2$	2.28	3.13			
	TIP DIAMETER, INCH	24.20	20.19			
	BLADE HEIGHT/MEAN DIAM. – MIN	0.084	0.099			
	– MAX	0.196	0.2			
	ADMISSION, PERCENT	100	100			
	PRESSURE RATIO	4.6	4.8			
TOTAL TURBINE FLOWRATE, LB/SEC		126.02	129.00	138.66	140.88	137.64
	OVERALL PRESSURE RATIO	20.1	20.1	20.1	20.1	20.1

* 1 IMPULSE STAGE, 1 REACTION STAGE

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ENGINE 3 - LOX/METHANE, METHANE COOLED

TURBOMACHINERY CANDIDATES

THE NEXT SEVEN CHARTS PRESENT THE RESULTS OF THE ENGINEERING SCREENING FOR ENGINE 3.

TURBOMACHINERY CANDIDATES

ENGINE 3 – LOX/METHANE, METHANE COOLED

PUMPS FOR ENGINE 3 - LOX/MEHTANE, METHANE COOLED

DUAL SHAFT CONFIGURATIONS

TWO DUAL SHAFT CONFIGURATIONS WERE CARRIED FORWARD FOR TURBINE SIZING AFTER THE PUMP SCREENING. THESE WERE METHANE MAIN PUMP + KICK PUMP WITH LOX MAIN PUMP ONLY (SYSTEM 3A), AND METHANE MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP + MAIN PUMP (SYSTEM 3B). THE FIRST OF THESE WAS THE MINIMUM POWER AND MINIMUM WEIGHT CONFIGURATION, WHILE THE SECOND SIGNIFICANTLY INCREASED THE LOX PUMP SPEED WITH ONLY A SLIGHT PENALTY IN REQUIRED POWER AND SYSTEM WEIGHT.

THE METHANE MAIN PUMP ONLY CONFIGURATION WAS DELETED AS IT REQUIRED SIGNIFICANTLY MORE POWER THAN THE MAIN PUMP + KICK PUMP CONFIGURATION.

THE METHANE CONFIGURATIONS WITH BOOST PUMPS WERE DELETED AS THE INCREASES IN MAIN PUMP SPEED WERE SMALL DUE TO BEARING DN LIMITS, AND WERE INSUFFICIENT TO OFFSET INCREASES IN REQUIRED POWER AND COMPLEXITY.

PUMPS FOR ENGINE 3 – LOX/METHANE, METHANE COOLED
DUAL SHAFT CONFIGURATIONS

SYSTEM IDENTIFIER	METHANE PUMP CONFIGURATION	LOX PUMP CONFIGURATION	CONCLUSIONS
	MAIN		DELETED • HIGH POWER REQUIREMENT
3A	MAIN + KICK	MAIN	CARRIED FORWARD • MINIMUM POWER, MINMUM WEIGHT
3B	MAIN + KICK	BOOST + MAIN	CARRIED FORWARD • MAXIMUM LOX PUMP SPEED
	BOOST + MAIN		DELETED • SPEED INCREASE INSUFFICIENT TO OFF SET INCREASE IN REQUIRED POWER AND COMPLEXITY
	BOOST + MAIN + KICK		DELETED • SPEED INCREASE INSUFFICIENT TO OFFSET INCREASE IN REQUIRED POWER AND COMPLEXITY

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PUMPS FOR ENGINE 3 - LOX/METHANE, METHANE COOLED

SINGLE SHAFT CONFIGURATIONS

TWO SINGLE SHAFT CONFIGURATIONS WERE CARRIED FORWARD FOR TURBINE SIZING. THESE WERE METHANE MAIN PUMP + KICK PUMP WITH LOX MAIN PUMP (SYSTEM 3C), AND METHANE MAIN PUMP + KICK PUMP WITH LOX BOOST PUMP + MAIN PUMP (SYSTEM 3D). THE FORMER WAS CARRIED FORWARD AS IT WAS A SIMPLE CONFIGURATION WITH THE SECOND LOWEST POWER REQUIREMENT, WHILE THE LATTER HAD MINIMUM REQUIRED POWER, MINIMUM SYSTEM WEIGHT AND SMALLEST DIAMETER.

CONFIGURATIONS INVOLVING A METHANE MAIN PUMP ALONE WERE DELETED AS THEY HAD THE HIGHEST POWER REQUIREMENT, LARGEST DIAMETERS AND MAXIMUM WEIGHTS. THE METHANE PUMP RUNS AT A SPEED MUCH LOWER THAN OPTIMUM DUE TO THE LOX PUMP SUCTION PERFORMANCE LIMITS, AND THIS SIGNIFICANTLY DEGRADES THE MAIN PUMP PERFORMANCE. IT SHOULD BE NOTED THAT THE SAME TRENDS ARE OBSERVED FOR THE MAIN PUMP + KICK PUMP, BUT THE SPECIFIC SPEEDS OF THESE PUMPS ARE HIGHER THAN FOR THE MAIN PUMP ALONE, AND THUS THE DECREASE IN ROTATIONAL SPEED IN THE SINGLE SHAFT CONFIGURATION DOES NOT REDUCE THE EFFICIENCY AS MUCH.

CONFIGURATIONS INVOLVING METHANE BOOST PUMPS WERE DELETED AS, IN ALL CASES, THE SHAFT SPEED WAS LIMITED BY THE LOX PUMP SUCTION PERFORMANCE AND A METHANE BOOST PUMP SERVES NO PURPOSE.

PUMPS FOR ENGINE 3 – LOX/ METHANE, METHANE COOLED

SINGLE SHAFT CONFIGURATIONS

SYSTEM IDENTIFIER	METHANE PUMP CONFIGURATION	LOX PUMP CONFIGURATION	CONCLUSIONS
	MAIN		DELETED • HIGH REQUIRED POWER
3C	MAIN + KICK	MAIN	CARRIED FORWARD • SIMPLE CONFIGURATION
3D	MAIN + KICK	BOOST + MAIN	CARRIED FORWARD • MINIMUM POWER, DIAMETER, WEIGHT
	BOOST + MAIN		DELETED • SPEED CONTROLLED BY LOX PUMP • METHANE BOOST PUMP NOT REQUIRED
	BOOST + MAIN + KICK		DELETED • SPEED CONTROLLED BY LOX PUMP • METHANE BOOST PUMP NOT REQUIRED

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TURBOMACHINERY FOR ENGINE 3 - LOX/METHANE, METHANE COOLDED

NO FURTHER SYSTEMS WERE DELETED IN THE TURBINE SCREENING PROCESS, AND THUS FOUR SYSTEMS WERE RECOMMENDED FOR LIFE CYCLE COST ANALYSIS.

BOTH TURBINES IN EACH OF THE DUAL SHAFT CONFIGURATIONS AND THE TURBINE FOR SYSTEM 3D WERE TWO ROW VELOCITY COMPOUNDED TURBINES WITH SLIGHT REACTION IN THE SECOND STAGE. THE TURBINE FOR CONFIGURATION 3C WAS A TWO STAGE PRESSURE COMPOUNDED TURBINE.

THE EXPECTED TRENDS ARE OBSERVED, EXCEPT FOR SYSTEM WEIGHT, WHERE THE SINGLE SHAFT CONFIGURATION WITHOUT BOOST PUMPS (SYSTEM 3C) IS SLIGHTLY HEAVIER THAN THE DUAL SHAFT CONFIGURATION WITHOUT BOOST PUMPS. THIS IS DUE TO THE SIGNIFICANTLY LARGER METHANE IMPELLERS REQUIRED FOR THE LOWER SPEED SINGLE SHAFT CONFIGURATION. FOR THIS ENGINE BOOST PUMPS INCREASE SYSTEM WEIGHT FOR THE DUAL SHAFT CONFIGURATIONS AND DECREASE SYSTEM WEIGHT FOR THE SINGLE SHAFT CONFIGURATIONS.

SYSTEM 3A HAS THE MINIMUM TURBINE FLOWRATE, SYSTEM 3B THE MINIMUM DIAMETER, SYSTEM 3C IS THE SIMPLEST CONFIGURATION, AND SYSTEM 3D HAS THE MINIMUM WEIGHT.

TURBOMACHINERY FOR ENGINE 3 – LOX/METHANE, METHANE COOLED

SUMMARY OF CANDIDATES

SYSTEM IDENTIFIER	METHANE PUMP CONFIG.	LOX PUMP CONFIG.	MAIN TURBOPUMP		SYSTEM WEIGHT LB	MAXIMUM DIAMETER INCH	COMPLEXITY FACTOR
			TURBINE ARRANGEMENT	TURBINE FLOWRATE LB/SEC			
3A	MAIN + KICK	MAIN	DUAL	133	2361	25.8	10
3B	MAIN + KICK	BOOST + MAIN	DUAL	135	2373	20.7	13
3C	MAIN + KICK	MAIN	SINGLE	176	2422	30.6	7
3D	MAIN + KICK	BOOST + MAIN	SINGLE	150	2179	26.3	10

86C-9-559

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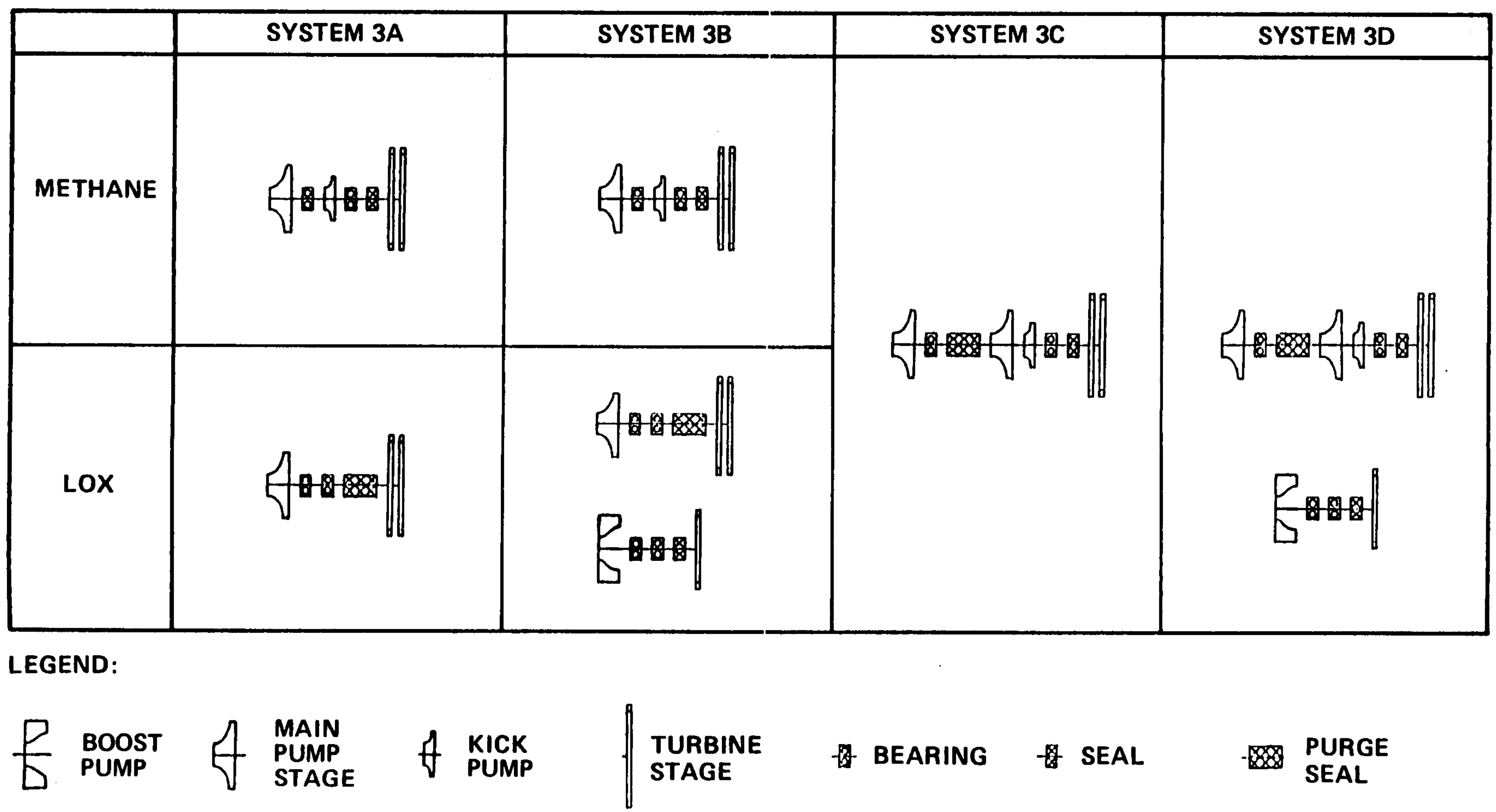
TURBOMACHINERY FOR ENGINE 3, LOX/METHANE, METHANE COOLED

SCHEMATICS OF CANDIDATES

THESE ARE THE SCHEMATICS OF THE FOUR ENGINE 3 TURBOMACHINERY SYSTEMS RECOMMENDED FOR LIFE CYCLE COST ANALYSIS.

C-2

TURBOMACHINERY FOR ENGINE 3 – LOX/METHANE, METHANE COOLED
SCHEMATICS OF CANDIDATES



86C-9-560

TURBOMACHINERY CANDIDATES FOR ENGINE 3-LOX/METHANE,

METHANE COOLED

SUMMARY OF PUMP DATA

DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE CANDIDATE PUMPS FOR ENGINE 3. PUMP ROTATIONAL SPEEDS WERE ALL SET BY SUCTION PERFORMANCE LIMITS.

TURBOMACHINERY CANDIDATES FOR ENGINE 3
LOX/METHANE, METHANE COOLED
SUMMARY OF PUMP DATA

SYSTEM		3A	3B	3C	3D
METHANE PUMP CONFIGURATION		M + K	M + K	M + K	M + K
LOX PUMP CONFIGURATION		M	B + M	M	B + M
TURBINE ARRANGEMENT		DUAL	DUAL	SINGLE	SINGLE
METHANE PUMPS	SPEED, RPM	20,000	20,000	9,500	13,000
	POWER, HP	43,401	43,401	58,222	50,198
	BEARING DN, 10^6 mm RPM	0.98	0.98	1.09	1.7
	SEAL RUBBING SPEED, FT/SEC	349	349	233	365
METHANE MAIN PUMP	FLOW, GPM	10,320	10,320	10,320	10,320
	HEAD, FT	26,315	26,315	26,315	26,315
	TIP DIAMETER, INCH	16.3	16.3	31.4	22.9
	NUMBER OF STAGES	1	1	1	1
METHANE KICK PUMP	FLOW, GPM	5,160	5,160	5,160	5,160
	HEAD, FT	7,258	7,258	7,258	7,258
	TIP DIAMETER, INCH	8.0	8.0	15.4	12.3
LOX MAIN PUMP	SPEED, RPM	9,500	13,000	9,500	13,000
	POWER, HP	39,723	40,525	39,723	42,230
	FLOW, GPM	11,514	11,514	11,514	11,514
	HEAD, FT	8,877	9,689	8,877	8,689
	TIP DIAMETER, INCH	19.3	14.7	19.30	14.1
	NUMBER OF STAGES	1	1	1	1
	BEARING DN, 10^6 mm RPM	.9	1.1	—	—
	SEAL RUBBING SPEED, FT/SEC	126	239	—	—
TOTAL SYSTEM POWER	HP	83,124	83,926	97,945	92,428
SYSTEM WEIGHT	LB	2,360	2,373	2,422	2,179

86C-9-562

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TURBOMACHINERY CANDIDATES FOR ENGINE 3 - LOX/METHANE, METHANE COOLED

SUMMARY OF TURBINE DATA

TURBINE DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE RECOMMENDED ENGINE 3 TURBOMACHINERY SYSTEMS. FOR THE LOX/METHANE DRIVE GASES THE BLADE SPEED IS SET TO OPTIMIZE U/CO WITHIN THE CONSTRAINT OF THE OTHER GROUNDRULES

TURBOMACHINERY CANDIDATES FOR ENGINE 3
LOX/METHANE, METHANE COOLED
SUMMARY OF TURBINE DATA

SYSTEM		3A	3B	3C	3D
METHANE PUMP CONFIGURATION		M+K	M+K	M+K	M+K
LOX PUMP CONFIGURATION		M	B+M	M	B+M
TURBINE ARRANGEMENT		DUAL	DUAL	SINGLE	SINGLE
METHANE OR SINGLE TURBINE	POWER, HP	43401	43401	97945	92428
	SPEED, RPM	20000	20000	9500	13000
	U/Co	0.250	0.250	0.206	0.25
	STAGING	2-MIXED*	2-MIXED*	2 SP C	2-MIXED*
	EFFICIENCY	0.730	0.730	0.666	0.737
	MEAN BLADE SPEED FT/SEC	994.	989.	1119.	1361.
	N^2 AA, 10^{10} RPM^2 $INCH^2$	1.86	1.85	2.73	2.91
	TIP DIAMETER, INCH	12.69	12.63	30.57	25.52
	BLADE HEIGHT/MEAN DIAM. – MIN	0.053	0.053	0.041	0.033
	MAX	0.114	0.115	0.132	0.063
	ADMISSION, PERCENT	100	100	100	100
	PRESSURE RATIO	4.2	4.1	20.1	20.1
LOX TURBINE	POWER, HP	39723	40525		
	SPEED, RPM	9500	13000		
	U/Co	0.251	0.251		
	STAGING	2-MIXED*	2-MIXED*		
	EFFICIENCY	0.729	0.729		
	MEAN BLADE SPEED, FT/SEC	951.	956.		
	N^2 AA, 10^{10} RPM^2 $INCH^2$	1.84	3.47		
	TIP DIAMETER, INCH	25.77	20.74		
	BLADE HEIGHT/MEAN DIAM. – MIN	0.054	0.100		
	MAX	0.123	0.2		
	ADMISSION, PERCENT	100	100		
	PRESSURE RATIO	4.7	4.8		
TOTAL TURBINE FLOWRATE, LB/SEC		133.20	134.49	176.24	150.20
	OVERALL PRESSURE RATIO	20.1	20.1	20.1	20.1

86C-9-584

*1 IMPULSE STAGE, 1 REACTION STAGE

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ENGINE 4-LOX/RP-1, LH_2 COOLED

TURBOMACHINERY CANDIDATES

THE NEXT NINE CHARTS PRESENT THE RESULTS OF THE ENGINEERING SCREENING FOR ENGINE 4.

TURBOMACHINERY CANDIDATES

ENGINE 4 – LOX/RP-1, LH_2 COOLED

PUMPS FOR ENGINE 4 - LOX/RP-1, LH_2 COOLED

DUAL SHAFT + HYDROGEN CONFIGURATIONS

FOUR PUMP CONFIGURATIONS FOR THE DUAL SHAFT + HYDROGEN TURBINE ARRANGEMENTS WERE CARRIED FORWARD AFTER THE PUMP SCREENING. EVERY CONFIGURATION CARRIED FORWARD USED A MAIN PUMP ONLY FOR THE HYDROGEN PUMP, AND THE RECOMMENDED CONFIGURATIONS WERE COMPRISED OF THE FOUR POSSIBLE COMBINATIONS OF RP-1 MAIN PUMP OR BOOST PUMP + MAIN PUMP, AND LOX MAIN PUMP OR BOOST PUMP + MAIN PUMP. THERE WAS VERY LITTLE DIFFERENCE IN TOTAL REQUIRED POWER FOR THE FOUR SYSTEMS. THE RP-1 MAIN PUMP WITH LOX MAIN PUMP CONFIGURATION (SYSTEM 4A) WAS THE SIMPLEST CONFIGURATION, THE CONFIGURATION WITH JUST THE LOX BOOST PUMP (SYSTEM 4B) HAD HIGH LOX PUMP SPEED, THE CONFIGURATION WITH JUST RP-1 BOOST PUMP (SYSTEM 4C) HAD HIGH RP-1 PUMP SPEED, AND THE CONFIGURATION WITH BOTH BOOST PUMPS (SYSTEM 4D) HAD MINIMUM POWER AND WEIGHT BUT MAXIMUM COMPLEXITY.

THE HYDROGEN PUMP CONFIGURATION OF BOOST PUMP + MAIN PUMP WAS DELETED, AS THE MAIN PUMP SPEED WAS LIMITED BY BEARING DN RATHER THAN SUCTION PERFORMANCE LIMITS, AND A BOOST PUMP WAS NOT REQUIRED.

PUMPS FOR ENGINE 4 – LOX/RP-1, LH_2 COOLED
DUAL SHAFT +HYDROGEN CONFIGURATIONS

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGURATION	RP-1 PUMP CONFIGURATION	LOX PUMP CONFIGURATION	CONCLUSIONS
	BOOST + MAIN			DELETED • SPEED LIMITED BY BEARING DN NOT SUCTION PERFORMANCE
4A	MAIN	MAIN	MAIN	CARRIED FORWARD • SIMPLE CONFIGURATION
4B	MAIN	MAIN	BOOST + MAIN	CARRIED FORWARD • COMBINES LOW POWER, MEDIUM COMPLEXITY AND HIGH LOX PUMP SPEED
4C	MAIN	BOOST + MAIN	MAIN	CARRIED FORWARD • COMBINES LOW POWER, MEDIUM COMPLEXITY AND HIGH RP-1 PUMP SPEED
4D	MAIN	BOOST + MAIN	BOOST + MAIN	CARRIED FORWARD • MINIMUM POWER

86C-9-564

PUMPS FOR ENGINE 4 - LOX/RP-1, LH_2 COOLED

SINGLE SHAFT + HYDROGEN CONFIGURATIONS

ONE PUMP CONFIGURATION FOR THE SINGLE SHAFT + HYDROGEN TURBINE ARRANGEMENTS WAS CARRIED FORWARD FOR TURBINE SIZING. THIS WAS THE HYDROGEN MAIN PUMP ONLY WITH RP-1 MAIN PUMP ONLY AND LOX BOOST PUMP + MAIN PUMP (SYSTEM 4E). THIS WAS CLEARLY THE BEST CONFIGURATION HAVING MAXIMUM SHAFT SPEED, MINIMUM REQUIRED POWER, MINIMUM WEIGHT AND MEDIUM COMPLEXITY.

CONFIGURATIONS INVOLVING THE HDYROGEN BOOST PUMP + MAIN PUMP WERE DELETED FOR THE REASONS STATED ON THE PREVIOUS CHART.

THE SIMPLEST CONFIGURATION OF THREE MAIN PUMPS WAS NOT CARRIED FORWARD AS IT HAD A SIGNIFICANTLY HIGHER POWER REQUIREMENT THAN SYSTEM 4E.

THE CONFIGURATIONS WITH RP-1 BOOST PUMPS WERE DELETED AS THE MAIN PUMP SHAFT SPEEDS WERE SET BY THE LOX PUMP SUCTION PERFORMANCE LIMITS AND THE RP-1 BOOST PUMPS SERVED NO PURPOSE.

PUMPS FOR ENGINE 4 – LOX/RP-1, LH_2 COOLED

SINGLE SHAFT + HYDROGEN CONFIGURATIONS

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGURATION	RP-1 PUMP CONFIGURATION	LOX PUMP CONFIGURATION	CONCLUSIONS
	BOOST + MAIN			DELETED • SPEED LIMITED BY BEARING DN NOT SUCTION PERFORMANCE
	MAIN	MAIN	MAIN	DELETED • LOW SPEED, HIGH POWER
4E	MAIN	MAIN	BOOST + MAIN	CARRIED FORWARD • MAXIMUM SPEED, MINIMUM POWER, MINIMUM WEIGHT
	MAIN	BOOST + MAIN	MAIN	DELETED • LOW SPEED, MAXIMUM POWER
	MAIN	BOOST + MAIN	BOOST + MAIN	DELETED • INCREASED POWER, WEIGHT AND COMPLEXITY OVER SYSTEM 4E WITH NO INCREASE IN SPEED • SPEED SET BY LOX PUMP

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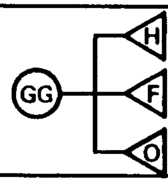
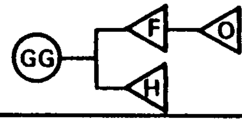
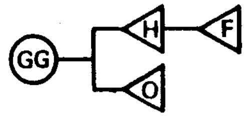
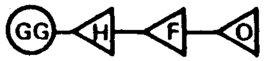
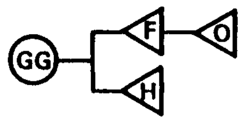
TURBOPUMPS FOR ENGINE 4 - LOX/RP-1, LH_2 COOLED

THE NEXT TWO CHARTS PRESENT THE RESULTS OF THE TURBINE SCREENING FOR ENGINE 4. SIX CONFIGURATIONS WERE RECOMMENDED FOR LIFE CYCLE COST ANALYSIS. THESE UTILIZED BOTH A PARALLEL TURBINE ARRANGEMENT, OR A MIXED SERIES/PARALLEL FOR THE DUAL SHAFT + HYDROGEN CONFIGURATIONS, AND A SERIES TURBINE ARRANGEMENT FOR EACH OF THREE PUMP CONFIGURATIONS. THE PUMP CONFIGURATIONS WERE THREE MAIN PUMPS ONLY WITH THE DUAL SHAFT + HYDROGEN TURBINE ARRANGEMENT (SYSTEM 4A/P AND 4A/S), HYDROGEN MAIN PUMP WITH RP-1 MAIN PUMP AND LOX BOOST PUMP + MAIN PUMP WITH THE DUAL SHAFT + HYDROGEN TURBINE ARRANGEMENT (SYSTEMS 4B/P AND 4B/S), AND HYDROGEN MAIN PUMP WITH RP-1 MAIN PUMP AND LOX BOOST PUMP + MAIN PUMP WITH THE SINGLE SHAFT + HYDROGEN TURBINE ARRANGEMENT.

THE 4A SYSTEMS WERE THE SIMPLEST DUAL SHAFT + HYDROGEN SYSTEMS, WITH THE SERIES TURBINE ARRANGEMENT HAVING THE MINIMUM FLOWRATE. THE 4B SYSTEMS HAD SMALL TURBINE DIAMETERS WITH THE SERIES SYSTEM ALSO HAVING THE MINIMUM FLOWRATE. THE 4E SYSTEMS HAD THE MINIMUM WEIGHT AND THE MINIMUM DIAMETER. THE PARALLEL CONFIGURATIONS WERE ALSO CARRIED OVER BECAUSE THERE WAS CONCERN ABOUT CONTROL OF THE SERIES SYSTEMS.

THE CONFIGURATIONS WITH RP-1 BOOST PUMP + MAIN PUMP WERE DELETED AS THE BENEFITS OF THE INCREASE IN RP-1 PUMP SPEED WERE INSUFFICIENT TO OFFSET THE INCREASE IN COMPLEXITY.

TURBOPUMPS FOR ENGINE 4 – LOX/RP-1, LH_2 COOLED

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGURATION	RP-1 PUMP CONFIGURATION	LOX PUMP CONFIGURATION	TURBINE ARRANGEMENT	CONCLUSIONS
					DELETED • HIGHEST TURBINE FLOWRATE
4 A/P	MAIN	MAIN	MAIN		CARRIED FORWARD • SIMPLE CONFIGURATION
	MAIN	MAIN	MAIN		DELETED • HIGHER TURBINE FLOWRATE THAN SYSTEM 4AP
4 A/S	MAIN	MAIN	MAIN		CARRIED FORWARD • MINIMUM TURBINE FLOWRATE
4 B/P	MAIN	MAIN	BOOST + MAIN		CARRIED FORWARD • LOW TURBINE FLOWRATE, SMALL DIAMETER
4 B/S	MAIN	MAIN	BOOST + MAIN		CARRIED FORWARD • MINIMUM TURBINE FLOWRATE, SMALL DIAMETER

86C-9-566

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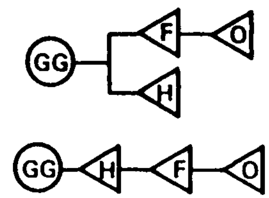
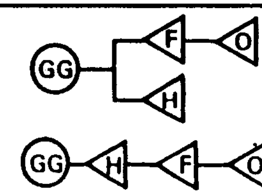
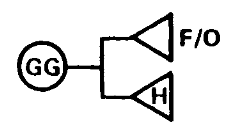
TURBOPUMPS FOR ENGINE 4 - LOX/RP-1, LH_2 COOLED (CONT'D)

THE PARALLEL ARRANGEMENT WAS DELETED BECAUSE IT REQUIRED THE HIGHEST TURBINE FLOWRATE FOR ALL PUMP CONFIGURATIONS.

THE COMBINED SERIES/PARALLEL ARRANGEMENT WAS ANALYZED FOR THE PUMP CONFIGURATION WITH THREE MAIN PUMPS, WITH BOTH THE HYDROGEN AND OXYGEN TURBINES ON THE PARALLEL LEG. A LOWER FLOWRATE WAS ACHIEVED WITH THE HYDROGEN TURBINE IN PARALLEL WITH THE SERIES FUEL AND OXIDIZER TURBINES, AND SO THIS ARRANGEMENT WAS USED FOR ALL THE COMBINED SERIES/PARALLEL ARRANGEMENTS.

THE TURBINES WERE MOSTLY TWO ROW VELOCITY COMPOUNDED TURBINES DUE TO THE U/CO VALUES ATTAINED WITH THE HIGH ENERGY LOX/HYDROGEN DRIVE GAS. HOWEVER, FOR THE SERIES ARRANGEMENTS, THE HYDROGEN TURBINE WAS EITHER TWO STAGE REACTION OR TWO STAGE PRESSURE COMPOUNDED AS THE PRESSURE RATIO ACROSS THE HYDROGEN TURBINE, AS THUS THE AVAILABLE ENERGY, WAS LOWER IN THESE CASES. IN ADDITION, THE RP-1 AND LOX TURBINES WERE PARTIAL ADMISSION DUE TO THE RELATIVELY LOW SHAFT SPEEDS OF THE PUMPS, THE HIGH BLADE SPEEDS AND THE LOW TURBINE FLOWRATES.

TURBOPUMPS FOR ENGINE 4 – LOX/RP-1, LH_2 COOLED

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGURATION	RP-1 PUMP CONFIGURATION	LOX PUMP CONFIGURATION	TURBINE ARRANGEMENT	CONCLUSIONS
	MAIN	BOOST + MAIN	MAIN		DELETED • BENEFITS OF INCREASED RP-1 PUMP SPEED INSUFFICIENT TO OFFSET INCREASED COMPLEXITY • MAXIMUM DIAMETER SET BY LOX PUMP TURBINE
	MAIN	BOOST + MAIN	BOOST + MAIN		DELETED • NO ADVANTAGE OVER SYSTEMS 4 B/P AND 4 B/S
4 E/P	MAIN	MAIN	BOOST + MAIN		CARRIED FORWARD • MINIMUM WEIGHT
4 E/S	MAIN	MAIN	BOOST + MAIN		CARRIED FORWARD • MINIMUM WEIGHT • LOWER TURBINE FLOWRATE THAN SYSTEM 4 E/P

86C-9-567

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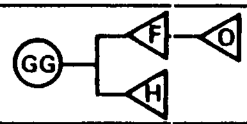
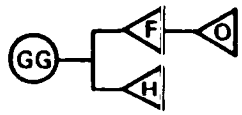
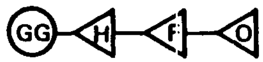
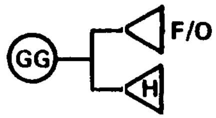
TURBOMACHINERY FOR ENGINE 4 - LOX/RP-1, LH_2 COOLED

SIX TURBOMACHINERY SYSTEMS WERE RECOMMENDED FOR LIFE CYCLE COST ANALYSIS FOR ENGINE 4.

THE EXPECTED TRENDS FOR THE DIFFERENT PUMP CONFIGURATIONS CAN BE SEEN, AS CAN A REDUCTION IN TURBINE FLOWRATE FOR THE SERIES TURBINE ARRANGEMENTS OVER THE COMBINED SERIES/PARALLEL TURBINE ARRANGEMENTS. FOR THIS ENGINE, ADDING A LOX BOOST PUMP DECREASES THE SYSTEM WEIGHT SLIGHTLY.

THE 4A AND 4E SYSTEMS WERE THE SIMPLEST, SYSTEM 4A/S REQUIRED THE SMALLEST TURBINE FLOWRATE, SYSTEM 4E/P HAD THE SMALLEST DIAMETER (SET BY THE TURBINE TIP DIAMETER IN ALL CASES) AND THE 4E SYSTEMS HAD THE MINIMUM WEIGHT.

TURBOMACHINERY FOR ENGINE 4 – LOX/RP-1, LH_2 COOLED
SUMMARY OF CANDIDATES

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGU-RATION	METHANE PUMP CONFIGU-RATION	LOX PUMP CONFIGU-RATION	TURBINE ARRANGEMENT	TURBINE FLOWRATE LB/SEC	SYSTEM WEIGHT LB	MAXIMUM DIAMETER INCH	COMPLEXITY FACTOR
4 A/P	MAIN	MAIN	MAIN		33.0	2541	43.3	13
4 A/S	MAIN	MAIN	MAIN		30.0	2541	42.8	13
4 B/P	MAIN	MAIN	BOOST + MAIN		32.8	2489	33.7	16
4 B/S	MAIN	MAIN	BOOST + MAIN		30.2	2489	31.4	16
4 E/P	MAIN	MAIN	BOOST + MAIN		38.7	2188	31.0	13
4 E/S	MAIN	MAIN	BOOST + MAIN		35.7	2188	31.2	13

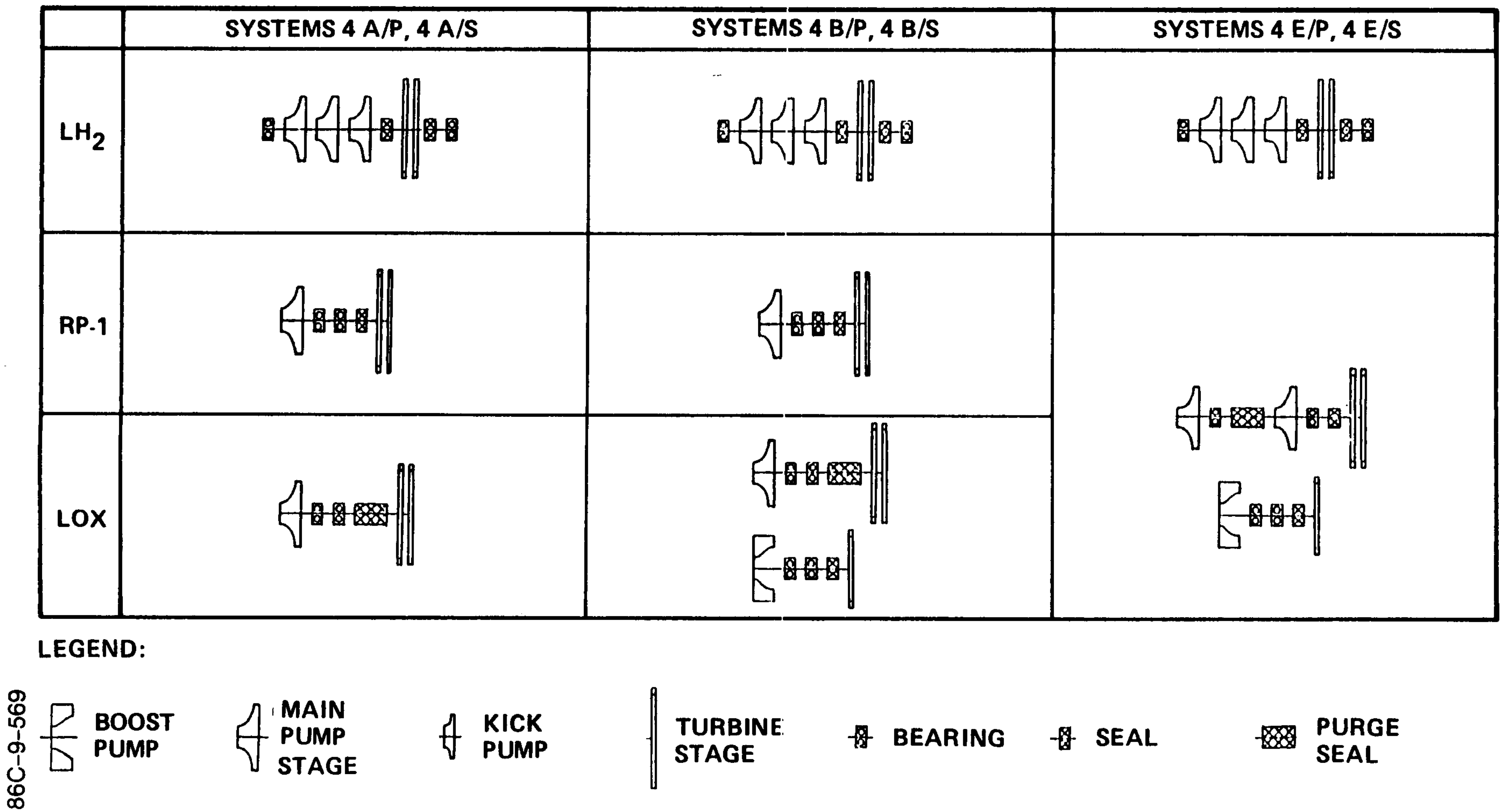
86C-9-568

TURBOMACHINERY FOR ENGINE 4 - LOX/RP-1, LH_2 COOLED

SCHEMATICS OF CANDIDATES

THESE ARE THE SCHEMATICS OF THE SIX ENGINE 4 TURBOMACHINERY SYSTEMS RECOMMENDED FOR LIFE CYCLE COST ANALYSIS

TURBOMACHINERY FOR ENGINE 4 – LOX/RP-1, LH_2 COOLED
SCHEMATICS OF CANDIDATES



TURBOMACHINERY CANDIDATES FOR ENGINE 4 –

LOX/RP-1, LH_2 COOLED

SUMMARY OF PUMP DATA

DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE CANDIDATE PUMPS FOR ENGINE 4. PUMP ROTATIONAL SPEEDS FOR THE RP-1 AND LOX PUMPS WERE SET BY SUCITON PERFORMANCE LIMITS, AND FOR THE HYDROGEN PUMPS WERE SET BY BEARING DN LIMITS. IT SHOULD BE NOTED THAT TO BETTER OPTIMIZE THE HYDROGEN PUMP SHAFT SPEED OUTBOARD BEARINGS WERE ASSUMED IN ORDER TO REDUCE THE BEARING DN.

TURBOMACHINERY CANDIDATES FOR ENGINE 4
LOX/RP-1, LH_2 COOLED
SUMMARY OF PUMP DATA

SYSTEM		4 A/P, 4 A/S	4 B/P, 4 B/S	4 E/P, 4 E/S
LH_2 PUMP CONFIGURATION		MAIN	M	M
RP-1 PUMP CONFIGURATION		M	M	M
LOX PUMP CONFIGURATION		M	B+M	B+M
TURBINE ARRANGEMENT		DUAL	DUAL	SINGLE
LH_2 PUMP	SPEED, RPM	60000	60000	60000
	POWER, HP	17165	17165	17165
	FLOW, GPM	3180	3180	3180
	HEAD, FT	205118	205118	205118
	TIP DIAMETER, INCH	7.56	7.56	7.56
	NUMBER OF STAGES	3	3	3
	BEARING DN, 10^6 MM RPM	2	2	2
	SEAL RUBBING SPEED, FT/SEC	430	430	430
RP-1 PUMP	SPEED, RPM	16800	16800	13500
	POWER, HP	24376	24376	26209
	FLOW, GPM	5644	5644	5644
	HEAD, FT	15663	15663	15663
	TIP DIAMETER, INCH	13.69	13.69	14.61
	NUMBER OF STAGES	1	1	1
	BEARING DN, 10^6 MM	1.2	1.2	1.3
	SEAL RUBBING SPEED, FT/SEC	253	253	281
LOX PUMP	SPEED, RPM	9650	13500	13500
	POWER, HP	45362	44704	44704
	FLOW, GPM	11140	11140	11140
	HEAD, FT	10604	11427	11427
	TIP DIAMETER, INCH	19.65	14.56	14.56
	NUMBER OF STAGES	1	1	1
	BEARING DN, 10^6 MM RPM	0.9	1.2	–
	SEAL RUBBING SPEED, FT/SEC	195	250	–
SYSTEM WEIGHT, LB		2541	2489	2188

86C-9-571

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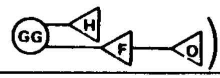
TURBOMACHINERY CANDIDATES FOR ENGINE 4 - LOX/RP-1, LH_2 COOLED

SUMMARY OF TURBINE DATA

DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE TURBINES FOR THE ENGINE 4 TURBOMACHINERY CANDIDATES. THE TURBINE BLADE SPEEDS ARE GENERALLY SET AT THE MAXIMUM ALLOWABLE VALUES DUE TO THE HIGH AVAILABLE ENERGY OF THE LOX/HYDROGEN DRIVE GAS AND THE DESIRE TO OPTIMIZE U/CO. THE LOW FLOWRATES, AND LARGE MEAN DIAMETERS COMBINE TO NECESSITATE PARTIAL ADMISSION FOR THE FUEL AND LOX TURBINES.

TURBOMACHINERY CANDIDATES FOR ENGINE 4
LOX/ RP-1, LH_2 COOLED
SUMMARY OF TURBINE DATA

SYSTEM		4 A/P	4 A/S	4 B/P	4 B/S	4 E/P	4 E/S
LH_2 PUMP CONFIGURATION		M	M	M	M	M	M
RP-1 PUMP CONFIGURATION		M	M	M	M	M	M
LOX PUMP CONFIGURATION		M	M	B+M	B+M	B+M	B+M
TURBINE ARRANGEMENT (PARALLEL DUAL SHAFT )		DUAL + HYDROGEN PARALLEL	DUAL + HYDROGEN SERIES	DUAL + HYDROGEN PARALLEL	DUAL + HYDROGEN SERIES	SINGLE + HYDROGEN PARALLEL	SINGLE + HYDROGEN SERIES
HYDROGEN TURBINE	POWER, HP	17165	17165	17165	17165	17165	17165
	SPEED, RPM	60000	60000	60000	60000	60000	60000
	U/Co	0.132	0.305	0.132	0.308	0.132	0.246
	STAGING	2 RV C	2-REACTION	2 RV C	2-REACTION	2 RV C	2 SPC
	EFFICIENCY	0.515	0.748	0.515	0.746	0.515	0.686
	MEAN BLADE SPEED, FT/SEC	1650.	1650.	1650.	1607.	1650.	1224.
	N^2 AA, 10^{10} RPM^2 $INCH^2$	5.56	4.22	5.56	4.29	5.56	4.53
	TIP DIAMETER, INCH	7.08	6.90	7.08	6.76	7.08	5.53
	BLADE HEIGHT/MEAN DIAM. – MIN	0.059	0.077	0.059	0.091	0.059	0.181
	– MAX	0.124	0.094	0.124	0.101	0.124	0.184
	ADMISSION, PERCENT	100	100	100	100	100	100
	TURBINE FLOWRATE, LB/SEC	7.51	30.0	7.51	30.2	7.51	35.72
	PRESSURE RATIO	20.5	1.5	20.5	1.5	20.5	1.4
RP-1 OR SINGLE TURBINE	POWER, HP	24376	24376	24376	24376	71304	71304
	SPEED, RPM	16800	16800	16800	16800	13500	13500
	U/Co	0.200	0.180	0.200	0.180	0.132	0.142
	STAGING	2 RV C	2 RV C	2 RV C	2 RV C	2 RV C	2-MIXED*
	EFFICIENCY	0.630	0.603	0.630	0.603	0.515	0.521
	MEAN BLADE SPEED, FT/SEC	1480.	1185.	1486.	1233.	1650.	1650.
	N^2 AA, 10^{10} RPM^2 $INCH^2$	5.19	3.61	5.15	3.70	4.88	4.90
	TIP DIAMETER, INCH	23.09	18.68	23.13	19.3	31.04	31.17
	BLADE HEIGHT/MEAN DIAM. – MIN	0.054	0.069	0.054	0.065	0.051	0.047
	– MAX	0.144	0.156	0.141	0.147	0.109	0.108
	ADMISSION, PERCENT	10	20	10	20	24	25
	TURBINE FLOWRATE, LB/SEC	25.52	30.0	25.27	30.2	31.18	35.72
	PRESSURE RATIO	2.2	2.0	2.2	2.1	20.5	14.7
LOX TURBINE	POWER, HP	45362	45362	44704	44704		
	SPEED, RPM	9650	9650	13500	13500		
	U/Co	0.157	0.171	0.157	0.174		
	STAGING	2-MIXED*	2 RV C	2-MIXED*	2 RV C		
	EFFICIENCY	0.560	0.583	0.560	0.584		
	MEAN BLADE SPEED, FT/SEC	1646.	1650.	1643.	1648.		
	N^2 AA, 10^{10} RPM^2 $INCH^2$	4.80	4.13	4.63	5.47		
	TIP DIAMETER, INCH	43.29	42.79	30.80	31.39		
	BLADE HEIGHT/MEAN DIAM. – MIN	0.050	0.036	0.048	0.048		
	– MAX	0.107	0.092	0.104	0.122		
	ADMISSION, PERCENT	10	20	20	30		
	TURBINE FLOWRATE, LB/SEC	25.52	30.0	25.27	30.2		
	PRESSURE RATIO	9.1	6.9	9.1	6.3		
TOTAL TURBINE FLOWRATE, LB/SEC		33.03	30.0	32.78	30.2	38.69	35.72
OVERALL PRESSURE RATIO		20.5	20.5	20.5	20.5		

*1 IMPULSE STAGE, 1 REACTION STAGE

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ENGINE 6-LOX/METHANE, LH_2 COOLED

TURBOMACHINERY CANDIDATES

THE NEXT NINE CHARTS PRESENT THE RESULTS OF THE ENGINEERING SCREENING FOR ENGINE 6.

TURBOMACHINERY CANDIDATES

ENGINE 6 – LOX/METHANE, LH_2 COOLED

PUMPS FOR ENGINE 6 – LOX/METHANE, LH_2 COOLED

DUAL SHAFT + HYDROGEN CONFIGURATIONS

TWO PUMP CONFIGURATIONS FOR THE DUAL SHAFT + HDYROGEN TURBINE ARRANGEMENT WERE CARRIED FORWARD AFTER THE PUMP SCREENING.

BOTH HAD MAIN PUMP ONLY CONFIGURATIONS FOR THE HYDROGEN AND METHANE PUMPS, WITH ONE HAVING A MAIN PUMP ONLY AND THE OTHER A BOOST PUMP + MAIN PUMP FOR THE LOX PUMP CONFIGURATION. THE TWO CONFIGURATIONS HAD ALMOST THE SAME POWER REQUIREMENT, WITH THE CONFIGURATION WITH THE LOX MAIN PUMP BEING SIMPLER, AND THAT WITH THE LOX BOOST PUMP + MAIN PUMP HAVING HIGHER SPEED AND SLIGHTLY LOWER WEIGHT.

THE HYDROGEN PUMP CONFIGURATION OF BOOST PUMP + MAIN PUMP WAS DELETED, AS THE MAIN PUMP SPEED WAS LIMITED BY BEARING DN RATHER THAN SUCTION PERFORMANCE LIMITS AND A BOOST PUMP WAS NOT REQUIRED.

THE METHANE PUMP CONFIGURATION OF BOOST PUMP + MAIN PUMP WAS DELETED AS OUTBOARD BEARINGS WERE REQUIRED IN THE MAIN PUMP TO SATISFY BEARING DN LIMITS. THE ADDED COMPLEXITY OF THIS AND THE BOOST PUMP OFFSET THE SIZE AND PERFORMANCE ADVANTAGES OF THE HIGHER MAIN PUMP SPEED.

PUMPS FOR ENGINE 6 – LOX/METHANE, LH_2 COOLED
DUAL SHAFT + HYDROGEN CONFIGURATIONS

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGURATION	METHANE PUMP CONFIGURATION	LOX PUMP CONFIGURATION	CONCLUSIONS
	BOOST + MAIN			DELETED • SPEED LIMITED BY BEARING DN NOT SUCTION PERFORMANCE
6A	MAIN	MAIN	MAIN	CARRIED FORWARD • SIMPLE CONFIGURATION
6B	MAIN	MAIN	BOOST + MAIN	CARRIED FORWARD • COMBINES LOW POWER, MEDIUM COMPLEXITY AND HIGH LOX PUMP SPEED
	MAIN	BOOST + MAIN		DELETED • OUTBOARD BEARING REQUIRED TO REDUCE DN • BENEFITS OF HIGHER PUMP SPEED INSUFFICIENT TO OFFSET INCREASED COMPLEXITY

86C-9-573

PUMPS FOR ENGINE 6 – LOX/METHANE, LH_2 COOLED

SINGLE SHAFT – HYDROGEN CONFIGURATIONS

ONE PUMP CONFIGURATION FOR THE SINGLE SHAFT + HYDROGEN TURBINE ARRANGEMENT WAS CARRIED FORWARD FOR TURBINE SIZING. THE CONFIGURATION WITH HDYROGEN MAIN PUMP, METHANE MAIN PUMP AND LOX BOOST PUMP + MAIN PUMP HAD THE LOWEST POWER REQUIREMENT AS WELL AS THE HIGHEST SPEED AND LOWEST WEIGHT.

CONFIGURATIONS INVOLVING THE HYDROGEN BOOST PUMP + MAIN PUMP WERE DELETED FOR THE REASONS STATED ON THE PREVIOUS CHART.

THE COMBINATION OF THREE MAIN PUMPS WAS DELETED AS THERE WAS A SIGNIFICANT SIZE AND PERFORMANCE PENALTY FOR THE METHANE PUMP WHEN IT WAS CONSTRAINED TO RUN AT THE SAME SPEED AS THE LOX PUMP.

CONFIGURATIONS INVOLVING THE METHANE BOOST PUMP + MAIN PUMP WERE DELETED AS THE MAIN PUMP SPEED IS SET BY THE LOX PUMP SUCTION PERFORMANCE LIMITS AND A METHANE BOOST PUMP IS NOT REQUIRED.

PUMPS FOR ENGINE 6 – LOX/METHANE, LH_2 COOLED
SINGLE SHAFT + HYDROGEN CONFIGURATIONS

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGURATION	METHANE PUMP CONFIGURATION	LOX PUMP CONFIGURATION	CONCLUSIONS
	BOOST + MAIN			DELETED • SPEED LIMITED BY BEARING DN NOT SUCTION PERFORMANCE
	MAIN	MAIN	MAIN	DELETED • SIGNIFICANT METHANE PUMP PERFORMANCE PENALTY
6C	MAIN	MAIN	BOOST + MAIN	CARRIED FORWARD • MINIMUM POWER AND WEIGHT
	MAIN	BOOST + MAIN		DELETED • SPEED CONTROLLED BY LOX PUMP • METHANE BOOST PUMP NOT REQUIRED

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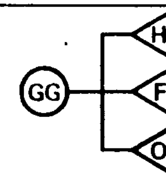
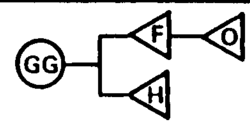
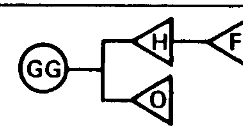
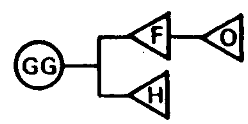
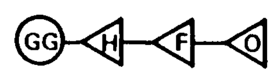
TURBOPUMPS FOR ENGINE 6 - LOX/METHANE, LH_2 COOLED

THE NEXT TWO CHARTS PRESENT THE RESULTS OF THE TURBINE SCREENING FOR ENGINE 6. SIX SYSTEMS WERE RECOMMENDED FOR LIFE CYCLE COST ANALYSIS. THESE UTILIZED BOTH A PARALLEL TURBINE ARRANGEMENT, OR A MIXED SERIES/PARALLEL FOR THE DUAL SHAFT + HYDROGEN CONFIGURATIONS, AND A SERIES TURBINE ARRANGEMENT FOR EACH OF THREE PUMP CONFIGURATIONS. THE PUMP CONFIGURATIONS WERE THREE MAIN PUMPS ONLY WITH THE DUAL SHAFT + HYDROGEN TURBINE ARRANGEMENT (SYSTEMS 6A/P AND 6A/S), HYDROGEN MAIN PUMP WITH METHANE MAIN PUMP AND LOX BOOST PUMP + MAIN PUMP WITH THE DUAL SHAFT + HYDROGEN TURBINE ARRANGEMENT (SYSTEMS 6B/P AND 6B/S), AND HYDROGEN MAIN PUMP WITH METHANE MAIN PUMP AND LOX BOOST PUMP + MAIN PUMP WITH THE SINGLE SHAFT + HYDROGEN TURBINE ARRANGEMENT (SYSTEMS 6C/P AND 6C/S).

THE 6A SYSTEMS WERE THE SIMPLEST DUAL SHAFT + HYDROGEN SYSTEMS, WITH THE SERIES TURBINE ARRANGEMENT HAVING THE MINIMUM FLOWRATE. THE 6B SYSTEMS HAD THE MINIMUM DIAMETERS AND THE SERIES TURBINE ARRANGEMENT ALSO HAD THE MINIMUM TURBINE FLOWRATE. THE 6C SYSTEMS HAD THE MINIMUM WEIGHT, AS WOULD BE EXPECTED FOR A SINGLE SHAFT CONFIGURATION. IN COMMON WITH ENGINE 4 THE PARALLEL TURBINE CONFIGURATIONS WERE CARRIED OVER PARTLY DUE TO CONCERN ABOUT CONTROL OF THE SERIES SYSTEMS.

TURBOPUMPS FOR ENGINE 6 – LOX/METHANE, LH_2 COOLED

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGURATION	METHANE PUMP CONFIGURATION	LOX PUMP CONFIGURATION	TURBINE ARRANGEMENT	CONCLUSIONS
					DELETED ● HIGHEST TURBINE FLOWRATE
6 A/P	MAIN	MAIN	MAIN		CARRIED FORWARD ● SIMPLE CONFIGURATION
	MAIN	MAIN	MAIN		DELETED ● HIGHER TURBINE FLOWRATE THAN SYSTEM 6 A/P
6 A/S	MAIN	MAIN	MAIN		CARRIED FORWARD ● MINIMUM TURBINE FLOWRATE
6 B/P	MAIN	MAIN	BOOST + MAIN		CARRIED FORWARD ● LOW TURBINE FLOWRATE, MINIMUM DIAMETER
6 B/S	MAIN	MAIN	BOOST + MAIN		CARRIED FORWARD ● MINIMUM TURBINE FLOWRATE, SMALL DIAMETER

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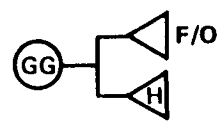
TURBOPUMPS FOR ENGINE 6, LOX/METHANE, LH_2 COOLED (CONT'D)

THE PARALLEL DUAL SHAFT + HYDROGEN ARRANGEMENT AND THE COMBINED SERIES/PARALLEL ARRANGEMENT WITH THE OXYGEN TURBINE ON THE PARALLEL LEG WERE DELETED FOR THE REASONS DESCRIBED PREVIOUSLY IN THE DISCUSSION OF THE ENGINE 4 CANDIDATES.

ALL THE TURBINES FOR THESE SYSTEMS WERE TWO ROW VELOCITY COMPOUNDED TURBINES EXCEPT FOR THE HYDROGEN TURBINES IN THE SERIES ARRANGEMENTS WHICH WERE 2 STAGE REACTION TURBINES. THE METHANE AND LOX TURBINES WERE PARTIAL ADMISSION DUE TO THE RELATIVELY LOW SHAFT SPEEDS OF THE PUMPS, THE HIGH BLADE SPEEDS AND THE LOW TURBINE FLOWRATES.

TURBOPUMPS FOR ENGINE 6 – LOX/METHANE, LH_2 COOLED

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGURATION	METHANE PUMP CONFIGURATION	LOX PUMP CONFIGURATION	TURBINE ARRANGEMENT	CONCLUSIONS
6 C/P	MAIN	MAIN	BOOST + MAIN		CARRIED FORWARD • MINIMUM WEIGHT
6 C/S	MAIN	MAIN	BOOST + MAIN		CARRIED FORWARD • MINIMUM WEIGHT • LOWER TURBINE FLOWRATE THAN SYSTEM 6 C/P

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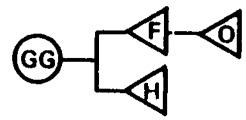
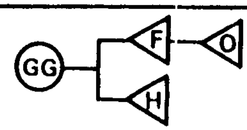
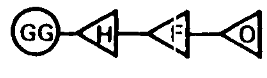
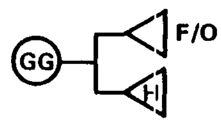
TURBOMACHINERY FOR ENGINE 6 - LOX/METHANE, LH_2 COOLED

SIX CONFIGURATIONS WERE CARRIED FORWARD FOR LIFE CYCLE COST ANALYSIS FOR ENGINE 6.

THE EXPECTED TRENDS FOR BOOST PUMP/NO BOOST PUMP, SINGLE SHAFT/DUAL SHAFT AND PARALLEL TURBINE/SERIES TURBINES ARE OBSERVED. FOR THIS ENGINE THE BOOST PUMPS SIGNIFICANTLY REDUCE THE MAXIMUM DIAMETER AND SLIGHTLY REDUCE THE SYSTEM WEIGHT.

SYSTEMS 6A/S AND 6B/S HAD THE MINIMUM TURBINE FLOWRATE, SYSTEM 6B/P HAD THE MINIMUM DIAMETER, THE 6C SYSTEMS HAD THE MINIMUM WEIGHT AND THE 6A AND 6C SYSTEMS HAD THE LOWEST COMPLEXITY.

TURBOMACHINERY FOR ENGINE 6
LOX/METHANE, LH_2 COOLED
SUMMARY OF CANDIDATES

SYSTEM IDENTIFIER	LH_2 PUMP CONFIGURATION	METHANE PUMP CONFIGURATION	LOX PUMP CONFIGURATION	TURBINE ARRANGEMENT	TURBINE FLOWRATE LB/SEC	SYSTEM WEIGHT LB	MAXIMUM DIAMETER INCH	COMPLEXITY FACTOR SHAFTS + ROTORS + PURGE SEALS
6 A/P	MAIN	MAIN	MAIN		43.5	2683	41.9	13
6 A/S	MAIN	MAIN	MAIN		40.2	2683	42.0	13
6 B/P	MAIN	MAIN	BOOST + MAIN		43.1	2624	29.5	16
6 B/S	MAIN	MAIN	BOOST + MAIN		40.2	2624	30.9	16
6 C/P	MAIN	MAIN	BOOST + MAIN		56.2	2449	30.4	13
6 C/S	MAIN	MAIN	BOOST + MAIN		49.1	2449	32.2	13

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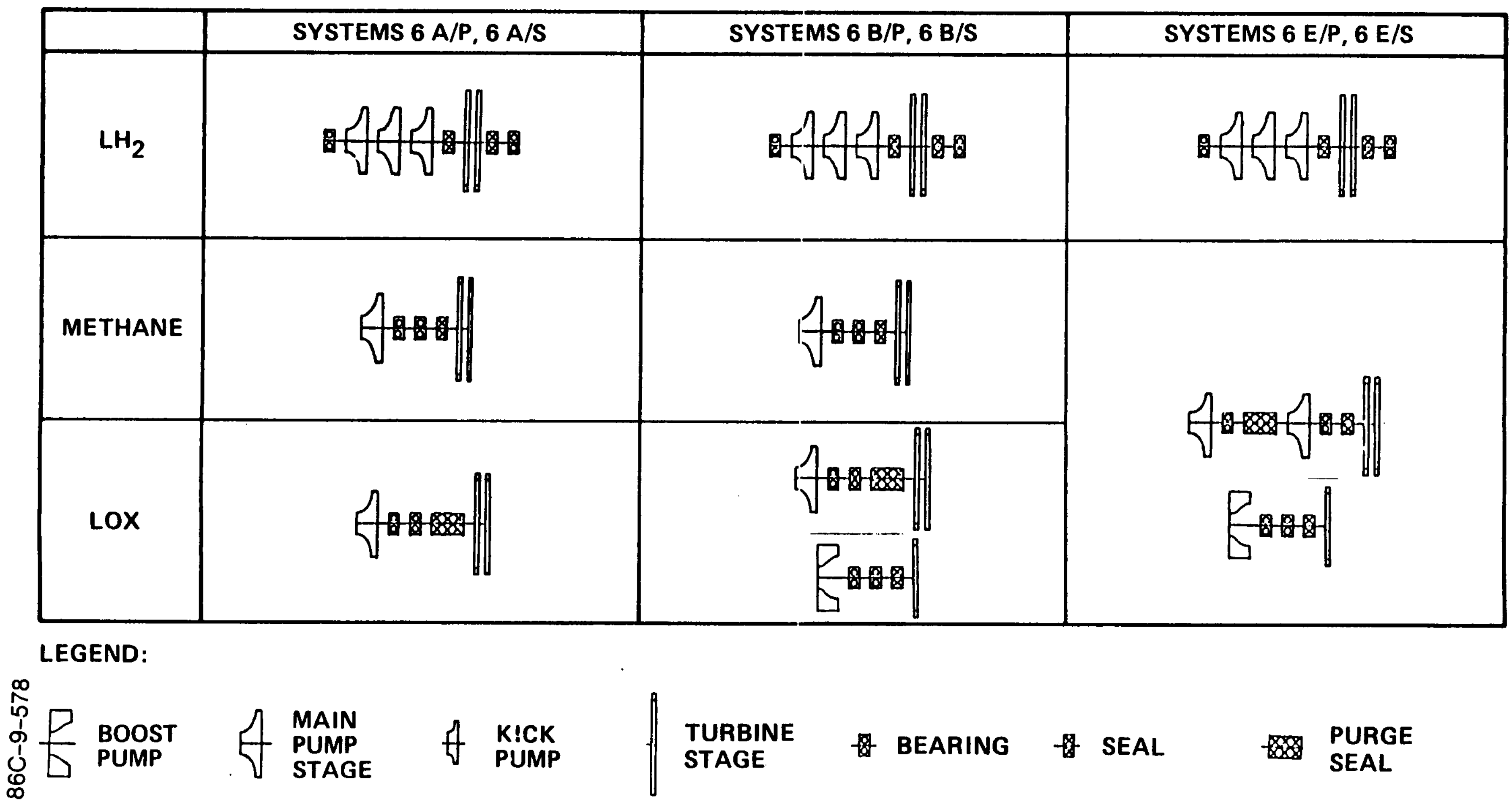
TURBOMACHINERY FOR ENGINE 6, LOX/METHANE, LH_2 COOLED

SCHEMATICS OF CANDIDATES

THESE ARE THE SCHEMATICS OF THE SIX ENGINE 6 TURBOMACHINERY SYSTEMS RECOMMENDED FOR LIFE CYCLE COST ANALYSIS

TURBOMACHINERY FOR ENGINE 6
LOX/METHANE, LH_2 COOLED
SCHEMATICS OF CANDIDATES



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TURBOMACHINERY CANDIDATES FOR ENGINE 6 -

LOX/METHANE, LH_2 COOLED

SUMMARY OF PUMP DATA

DESIGN PARAMETERS AND CHARACTERISTICS ARE PRESENTED FOR THE CANDIDATE PUMPS FOR ENGINE 6. PUMP ROTATIONAL SPEEDS ARE SET BY PUMP SUCTION PERFORMANCE LIMITS, EXCEPT FOR THE HYDROGEN PUMPS WHICH ARE SET BY BEARING DN LIMITS. IT SHOULD BE NOTED THAT OUTBOARD BEARINGS WERE ASSUMED FOR THE HYDROGEN PUMPS TO REDUCE BEARING DN VALUES.

TURBOMACHINERY CANDIDATES FOR ENGINE 6
LOX/METHANE, LH_2 COOLED
SUMMARY OF PUMP DATA

SYSTEM		6 A/B, 6 A/S	6 B/B, 6 B/S	6 C/P, 6 C/S
LH_2 PUMP CONFIGURATION		M	M	M
CH_4 PUMP CONFIGURATION		M	M	M
LOX PUMP CONFIGURATION		M	B+M	B+M
TURBINE ARRANGEMENT		DUAL	DUAL	SINGLE
LH_2 PUMP	SPEED, RPM	60000	60000	60000
	POWER, HP	20612	20612	20612
	FLOW, GPM	3910	3910	3910
	HEAD, FT	204762	204762	204762
	TIP DIAMETER, INCH	7.6	7.6	7.6
	NUMBER OF STAGES	3	3	3
	BEARING DN, 10^6 MM RPM	2	2	2
	SEAL BEARING SPEED, FT/SEC	430	430	430
CH_4 PUMP	SPEED, RPM	21900	21900	13400
	POWER, HP	37682	37682	46134
	FLOW, GPM	8629	8629	8629
	HEAD, FT	29903	29903	29903
	TIP DIAMETER, INCH	14.5	14.5	23.72
	NUMBER OF STAGES	1	1	1
	BEARING DN, 10^6MM RPM	1.6	1.6	1.4
	SEAL RUBBING SPEED, FT/SEC	344	344	297
LOX PUMP	SPEED, RPM	9580	13400	13400
	POWER, HP	46479	45742	45742
	FLOW, GPM	11296	11296	11296
	HEAD, FT	10694	11518	11578
	TIP DIAMETER, INCH	19.89	14.72	14.72
	NUMBER OF STAGES	1	1	1
	BEARING DN, 10^6MM RPM	0.9	1.2	–
	SEAL RUBBING SPEED, FT/SEC	195	250	–
TOTAL POWER, HP		104773	104036	112488
SYSTEM WEIGHT, LB		2683	2624	2449

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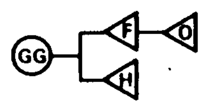
TURBOMACHINERY CANDIDATES FOR ENGINE 6 – LOX/METHANE, LH_2 COOLED

SUMMARY OF TURBINE DATA

DESIGN PARAMETERS AND CHARACTERISTICS FOR THE TURBINES FOR THE TURBOMACHINERY CANDIDATES FOR ENGINE 6 ARE PRESENTED. THE TURBINE BLADE SPEEDS ARE GENERALLY SET CLOSE TO THE MAXIMUM ALLOWABLE VALUES DUE TO THE HIGH AVAILABLE ENERGY OF THE LOX/HYDROGEN DRIVE GAS AND THE DESIRE TO OPTIMIZE U/CO. THE LOW TURBINE FLOWRATES, AND LARGE MEAN DIAMETERS COMBINE TO NECESSITATE PARTIAL ADMISSION FOR THE FUEL AND LOX TURBINES.

TURBOMACHINERY CANDIDATES FOR ENGINE 6
LOX/METHANE, LH_2 COOLED
SUMMARY OF TURBINE DATA



SYSTEM		6 A/P	6 A/S	6 B/P	6 B/S	6 E/P	6 E/S
LH_2 PUMP CONFIGURATION		M	M	M	M	M	M
METHANE PUMP CONFIGURATION		M	M	M	M	M	M
LOX PUMP CONFIGURATION		M	M	B+M	B+M	B+M	B+M
TURBINE ARRANGEMENT (PARALLEL DUAL SHAFT)		DUAL + HYDROGEN PARALLEL	DUAL + HYDROGEN SERIES	DUAL + HYDROGEN PARALLEL	DUAL + HYDROGEN SERIES	SINGLE + HYDROGEN PARALLEL	SINGLE + HYDROGEN SERIES
HYDROGEN TURBINE	POWER, HP	20612	20612	20612	20612	20612	20612
	SPEED, RPM	60000	60000	60000	60000	60000	60000
	U/Co	0.142	0.308	0.142	0.308	0.142	0.354
	STAGING	2 RV C	2-REACTION	2 RV C	2-REACTION	2 RV C	2-REACTION
	EFFICIENCY	0.543	0.747	0.543	0.747	0.543	0.683
	MEAN BLADE SPEED, FT/SEC	1650.	1520.	1650.	1506.	1650.	1650.
	N^2 AA, 10^{10} RPM^2 $INCH^2$	7.30	5.59	7.30	5.54	7.30	4.85
	TIP DIAMETER, INCH	7.32	6.66	7.32	6.60	7.32	6.98
	BLADE HEIGHT/MEAN DIAM. – MIN	0.075	0.126	0.075	0.130	0.075	0.085
	– MAX	0.163	0.147	0.163	0.148	0.163	0.108
	ADMISSION, PERCENT	100	100	100	100	100	100
	TURBINE FLOWRATE, LB/SEC	9.96	40.20	9.96	40.20	9.96	49.11
	PRESSURE RATIO	20.3	1.5	20.3	1.5	20.3	1.4
METHANE OR SINGLE TURBINE	POWER, HP	37682	37682	37682	37682	91878	91878
	SPEED, RPM	21900	21900	21900	21900	13400	13400
	U/Co	0.198	0.200	0.198	0.200	0.142	0.152
	STAGING	2 RV C	2 RV C	2 RV C	2 RV C	2 RV C	2-MIXED*
	EFFICIENCY	0.627	0.630	0.627	0.630	0.521	0.569
	MEAN BLADE SPEED , FT/SEC	1569.	1455.	1586.	1466.	1650.	1641.
	N^2 AA, 10^{10} RPM^2 $INCH^2$	3.52	2.92	3.52	2.92	3.38	6.46
	TIP DIAMETER, INCH	17.84	17.01	18.00	17.10	30.37	32.15
	BLADE HEIGHT/MEAN DIAM. – MIN	0.033	0.044	0.032	0.043	0.035	0.062
	– MAX	0.087	0.117	0.085	0.115	0.075	0.145
	ADMISSION, PERCENT	35	50	35	50	50	25
	TURBINE FLOWRATE, LB/SEC	33.52	40.20	33.13	40.20	46.27	49.11
	PRESSURE RATIO	3.0	2.7	3.1	2.8	20.3	14.3
LOX TURBINE	POWER, HP	46479	46479	45742	45742		
	SPEED, RPM	9580	9580	13400	13400		
	U/Co	0.182	0.200	0.182	0.200		
	STAGING	2-MIXED*	2 RV C	2-MIXED*	2 RV C		
	EFFICIENCY	0.612	0.625	0.612	0.625		
	MEAN BLADE SPEED, FT/SEC	1629.	1611.	1617.	1607.		
	N^2 AA, 10^{10} RPM^2 $INCH^2$	3.33	3.88	2.87	3.81		
	TIP DIAMETER, INCH	41.92	42.03	29.50	30.92		
	BLADE HEIGHT/MEAN DIAM. – MIN	0.036	0.032	0.031	0.044		
	– MAX	0.076	0.091	0.066	0.125		
	ADMISSION, PERCENT	20	35	45	50		
	TURBINE FLOWRATE, LB/SEC	33.52	40.20	33.13	40.20		
	PRESSURE RATIO	6.6	4.9	6.4	4.8		
TOTAL TURBINE FLOWRATE, LB/SEC		43.48	40.20	43.09	40.20	56.23	49.11
OVERALL PRESSURE RATIO		20.3	20.3	20.3	20.3	20.3	20.3

* 1 IMPULSE STAGE, 1 REACTION STAGE

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TURBOPUMP SCREENING SUMMARY

THIS TABLE SUMMARIZES THE RESULTS OF THE PUMP AND TURBINE SCREENING FOR THE FOUR ENGINES FOR WHICH IT HAS BEEN COMPLETED.

FOR EACH ENGINE IT SHOWS THE TOTAL NUMBER OF TURBOMACHINERY SYSTEMS RECOMMENDED FOR LIFE CYCLE COST ANALYSIS, THE TOTAL NUMBER OF EACH PUMP CONFIGURATION USED IN THOSE SYSTEMS, AND HOW MANY UTILIZE DUAL SHAFT AND SINGLE SHAFT TURBINE ARRANGEMENTS WITH SERIES OR PARALLEL HYDROGEN TURBINES (WHEN REQUIRED).

TURBOPUMP SCREENING SUMMARY

ENGINE	TOTAL NUMBER OF CANDIDATES	PUMPS								TURBINES			
		FUEL				LOX		LH_2		DUAL SETS	SINGLE	HYDROGEN	
		M	B&M	M&K	B&M&K	M	B&M	M	B&M			SERIES	PARALLEL
1	5	0	0	4	1	2	3	–	–	2	3	–	–
3	4	0	0	4	0	2	2	–	–	2	2	–	–
4	6	6	0	0	0	2	4	6	0	4	2	3	3
6	6	6	0	0	0	2	4	6	0	4	2	3	3

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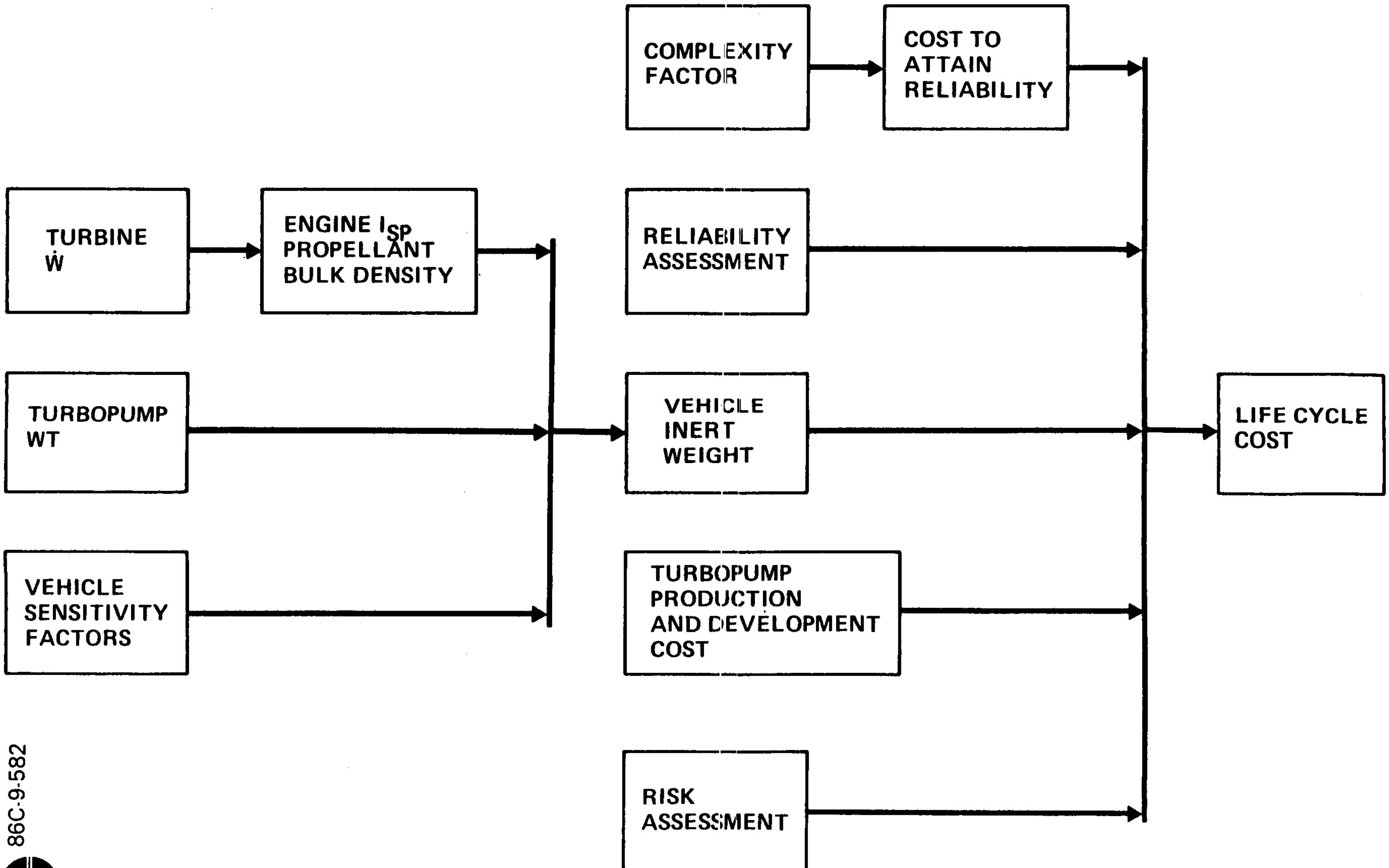
FINAL CONFIGURATION SELECTION LOGIC

FOR EACH ENGINE, THE CANDIDATE TURBOPUMPS THAT SURVIVE THE SCREENING PROCESS MUST UNDERGO A SELECTION PROCEDURE TO DETERMINE THE OPTIMUM CONFIGURATION. THIS IS THE FLOW CHART FOR THE SELECTION PROCEDURE. THE TURBINE FLOWRATE AND TURBOPUMP WEIGHT FOR EACH CANDIDATE ARE TRANSLATED INTO VEHICLE INERT WEIGHT USING ENGINE SENSITIVITY FACTORS FROM THE BASELINE ENGINE BALANCES AND VEHICLE SENSITIVITY FACTORS FROM THE SPACE TRANSPORTATION ARCHITECTURE STUDIES (STAS) VEHICLE ANALYSES. NEXT, ASSESSMENTS OF RELIABILITY, COMPLEXITY, RISK, AND PRODUCTION AND DEVELOPMENT COSTS ARE MADE FOR EACH TURBOPUMP CANDIDATE. COST ALGORITHMS ARE THEN USED TO TRANSLATE THESE ASSESSMENTS AND THE VEHICLE INERT WEIGHT INTO AN OVERALL VEHICLE LIFE CYCLE COST IMPACT FOR EACH TURBOPUMP CANDIDATE. THIS PROVIDES A SINGLE PARAMETER FOR RUNNING THE CANDIDATE TUROPUMPS FOR EACH ENGINE.

FINAL CONFIGURATION SELECTION LOGIC



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THROTTLING REQUIREMENT EVALUATION

THE TURBOMACHINERY SYSTEMS ARE SIZED FOR THE 750K THRUST OPERATING POINT, BUT MUST ALSO OPERATE EFFICIENTLY AND WITH SUFFICIENT MARGIN AT 625K THRUST. THIS THROTTLING REQUIREMENT, HOWEVER, SHOULD NOT AFFECT THE SELECTION PROCESS SIGNIFICANTLY AS THE OFF DESIGN PERFORMANCE OF ALL THE CANDIDATE SYSTEMS FOR AN ENGINE SHOULD BE SIMILAR. THE SELECTED SYSTEM FOR EACH ENGINE WILL BE ANALYZED AT THE 625K THRUST OPERATING POINT TO ENSURE ACCEPTABLE EFFICIENCY, STALL MARGIN AND SUCTION PERFORMANCE AT THAT POINT.

THROTTLING REQUIREMENT EVALUATION

- **SYSTEMS SIZED FOR 750K BALANCES**
- **THROTTLING REQUIREMENTS SHOULD NOT AFFECT SYSTEM RELATIVE MERIT**
    - COMPONENT OFF-DESIGN PERFORMANCE SIMILAR FOR HYDRODYNAMIC AND AERODYNAMIC DESIGN PARAMETERS
- **SELECTED TURBOMACHINERY SYSTEMS ANALYZED AT 625K OPERATING POINT TO ENSURE ACCEPTABLE CHARACTERISTICS**

TE-104

STBE CONFIGURATION STUDY
SECOND QUARTERLY REVIEW
AGENDA

- INTRODUCTION .... F. KIRBY
- TASK 1 SUMMARY .... A. WEISS
- TASK 2 STATUS REVIEW
  - SUBSYSTEM OPTIMIZATION APPROACH .... A. WEISS
  - TURBOMACHINERY STUDIES .... A. EASTLAND
  - COMBUSTION DEVICES STUDIES .... P. MEHEGAN
  - THROTTLING ON-DESIGN/OFF-DESIGN STUDY .... W. BISSELL, D. NGUYEN
  - CONTROL SYSTEM AND HEALTH MONITOR STUDIES .... R. BREWSTER
- SUMMARY .... A. WEISS

86C-9-681-5

STBE COMBUSTION DEVICES

DURING THE TASK 2 STBE STUDIES, FOUR MAJOR COMBUSTION DEVICES COMPONENTS ARE ADDRESSED; THE MAIN INJECTOR, COMBUSTION CHAMBER/NOZZLE, GAS GENERATOR, AND THE IGNITION SYSTEM.

COMBUSTION DEVICES AGENDA

- MAIN INJECTOR
- COMBUSTION CHAMBER/NOZZLE
- GAS GENERATOR
- IGNITION SYSTEM

COMBUSTION DEVICES STUDY PLAN

THE PRIMARY OBJECTIVE OF THE COMBUSTION DEVICES PLAN IS TO SELECT OPTIMUM LOX/HC COMBUSTION DEVICES CONFIGURATIONS FOR EACH CANDIDATE.

THE APPROACH IS LISTED ON THIS CHART

COMBUSTION DEVICES STUDY PLAN

- **OBJECTIVE**
  - SELECT OPTIMUM LOX/HC COMBUSTION DEVICES CONFIGURATION FOR EACH CANDIDATE
- **APPROACH**
  - USE 1986 TECHNOLOGY
  - DEFINE BASELINE ENGINE BALANCE
  - IDENTIFY POTENTIAL DESIGN CONCEPTS
  - SELECT BASELINE CONFIGURATION
  - EVALUATE BASELINE AND ALTERNATES AGAINST TRADEOFF FACTORS
    - PERFORMANCE
    - WEIGHT
    - COST
    - TECHNICAL RISK
  - RECOMMEND BEST CONFIGURATION

86D-9-1918

ENGINE OPERATING CONDITIONS

THE BASIC ENGINE OPERATING CONDITIONS FOR THE 6 CANDIDATE 1995 IOC CONCEPTS ARE LISTED ON THIS CHART. THE PROPELLANT COMBINATION, THE CHAMBER COOLANT AND THE CHAMBER PRESSURE ARE KEY ITEMS

ENGINE OPERATING CONDITIONS

ENGINE CONFIGURATION NUMBER	1	2	3	4	5	6
ENGINE CYCLE TYPE	1	2	2	3	3	3
T/C PROPELLANT COMBINATION	LOX/RP-1	LOX/C_3H_8	LOX/CH_4	LOX/RP-1	LOX/C_3H_8	LOX/CH_4
REGENERATIVE COOLANT	RP-1	C_3H_8	CH_4	H_2	H_2	H_2
THRUST, SL (klbf)	750	750	750	750	750	750
THRUST, VAC (klbf)	867	854	852	846	846	856
SPECIFIC IMPULSE, VAC (s)	329	345	350	349	357	361
COMBUSTION C* EFFICIENCY (%)	96	97	97	96	97	97
CHAMBER PRESSURE (psia)	2350	3407	3495	4165	4170	4200

86D-9-1919

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TYPICAL STBE ENGINE SCHEMATICS

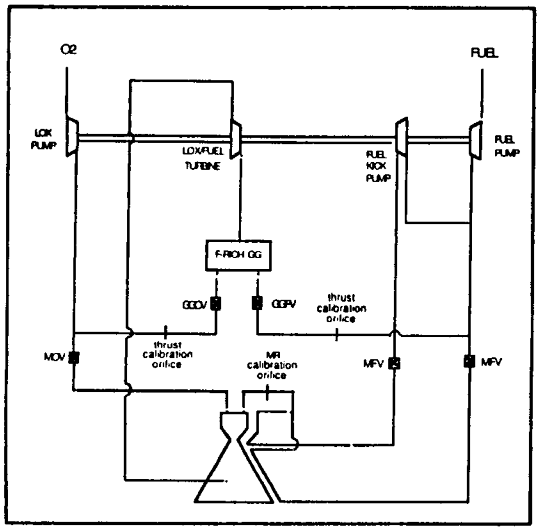
THE FOLLOWING 3 CYCLES ARE THE GAS GENERATOR CYCLE CANDIDATES FOR THE 1995 ENGINES. ALL ARE FUEL COOLED (EITHER HYDROCARBON OR HYDROGEN). THE FIRST (CYCLE TYPE 1) IS A SINGLE SHAFT UNIT FOR LOX/RP-1. EXCEPT FOR THE PARALLEL COOLANT FLOW CIRCUIT, IT IS SIMILAR TO THE SCHEMATIC FOR THE F-1 ENGINE. THE HIGH DENSITY OF RP-1 MAKES THE SINGLE SHAFT TURBOPUMP FEASIBLE.

THE SECOND CYCLE IS THE SAME BASIC FLOW CIRCUIT WITH THE DUAL SHAFT TURBOMACHINERY THAT IS ATTRACTIVE FOR FUELS THAT ARE LOWER IN DENSITY THAN RP-1. THE SERIES TURBINE ARRANGEMENT IMPROVES PERFORMANCE SIGNIFICANTLY.

THE THIRD CYCLE IS THE FLOW CIRCUIT FOR THE HYDROGEN COOLED CASES. TO AVOID THE USE OF 3 TURBOPUMPS, THE SINGLE SHAFT ARRANGEMENT WAS USED FOR THE TWO MAIN PROPELLANTS, THE LOX AND THE HYDROCARBON. THE HYDROGEN TURBOPUMP IS A FAR SMALLER UNIT WITH ITS TURBINE IN PARALLEL WITH THE MAIN TURBINE.

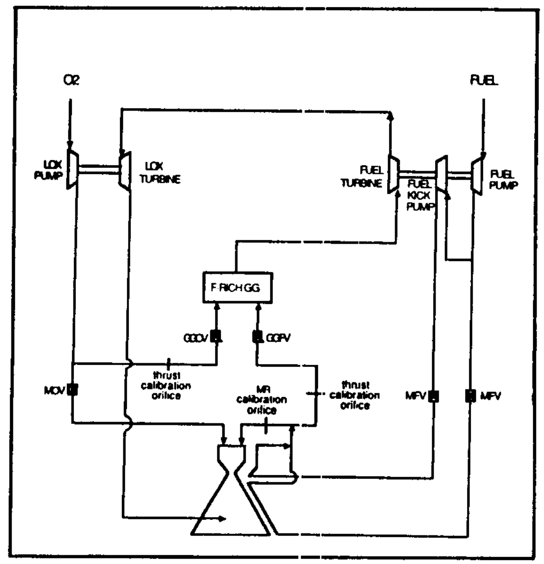
TYPICAL STBE ENGINE SCHEMATICS

CYCLE TYPE 1 (ENGINE 1)



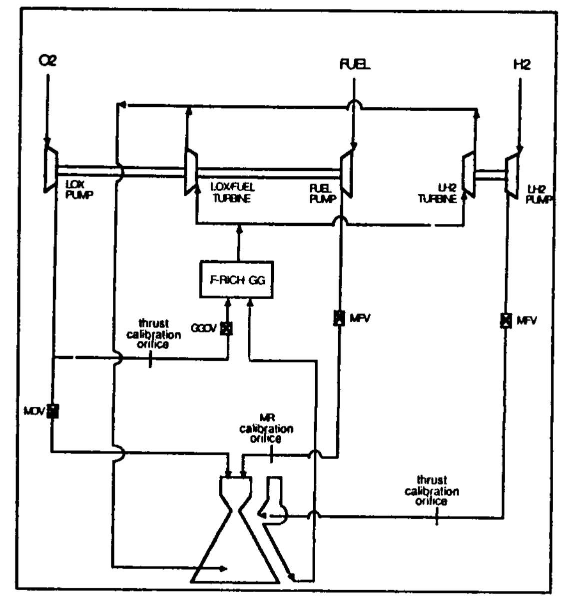
- GAS GENERATOR CYCLE
- FUEL COOLED
- LIQUID/LIQUID INJECTION

CYCLE TYPE 2 (ENGINES 2 AND 3)



- GAS GENERATOR CYCLE
- FUEL COOLED
- LIQUID PROPANE INJECTION
- GASEOUS METHANE INJECTION

CYCLE TYPE 3 (ENGINES 4, 5, AND 6)



- GAS GENERATOR CYCLE
- LIQUID HYDROGEN COOLED
- LIQUID/LIQUID INJECTION

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MAIN INJECTOR

MAIN INJECTOR DESIGN CONSIDERATIONS

THE MAJOR DESIGN CONSIDERATION FOR THE MAIN INJECTOR ARE LISTED HERE

MAIN INJECTOR DESIGN CONSIDERATIONS

- **INJECTOR OPERATIONS CONDITIONS**
- **INJECTOR ELEMENT DESIGN**
  - SELECTION OF INJECTION ELEMENT
  - ARRANGEMENT OF ELEMENTS
- **COMBUSTION STABILITY CONSIDERATIONS**

MAIN INJECTOR OPERATING CONDITIONS

THE MAIN INJECTOR OPERATING CONDITIONS AND SIZES ARE TABULATED ON THIS CHART.
PERFORMANCE, P_c, AND FUEL INJECTION STATE ARE HIGHLIGHTED

MAIN INJECTOR OPERATING CONDITIONS

ENGINE CONFIGURATION NUMBER	1	2	3	4	5	6
PROPELLANT COMBINATION	LOX/RP-1	LOX/C_3H_8	LOX/CH_4	LOX/RP-1	LOX/C_3H_8	LOX/CH_4
Nc*, %	96	97	97	96	97	97
Pc, psia	2350	3407	3495	4165	4170	4200
W Ox, lb/s	1827	1773	1790	1758	1759	1775
W Fl, lb/s	652	572	511	628	567	507
MR, O/F	2.8	3.1	3.5	2.8	3.1	3.5
P INJ Ox, psia	2850	4089	4194	4998	5004	5040
T INJ Ox, °R	163	163	163	163	163	163
P INJ Fl, psia	2820	4089	4194	4998	5004	5040
T INJ Fl, °R	969	611	534	520	160	210
FUEL INJ STATE	LIQ	LIQ	GAS	LIQ	LIQ	LIQ
INJECTOR DIAMETER, in.	25.3	20.7	20.4	18.7	18.6	18.6

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INJECTOR ELEMENT DESIGN

PRIMARY INJECTOR ELEMENT DESIGN CONSIDERATIONS AND CANDIDATE INJECTION ELEMENT TYPES ARE PRESENTED FOR LIQUID/LIQUID AND GAS/LIQUID PROPELLANT COMBINATIONS

INJECTOR ELEMENT DESIGN

- **CONSIDERATIONS**
  - PERFORMANCE
  - STABILITY
  - HARDWARE COMPATIBILITY
  - PRODUCIBILITY
  - DURABILITY
  - EXPERIENCE
- **CANDIDATE ELEMENTS**
  - LIQUID/LIQUID
    - LIKE IMPINGING
    - UNLIKE IMPINGING
    - NONIMPINGING
  - GAS/LIQUID
    - IMPINGING
    - NONIMPINGING

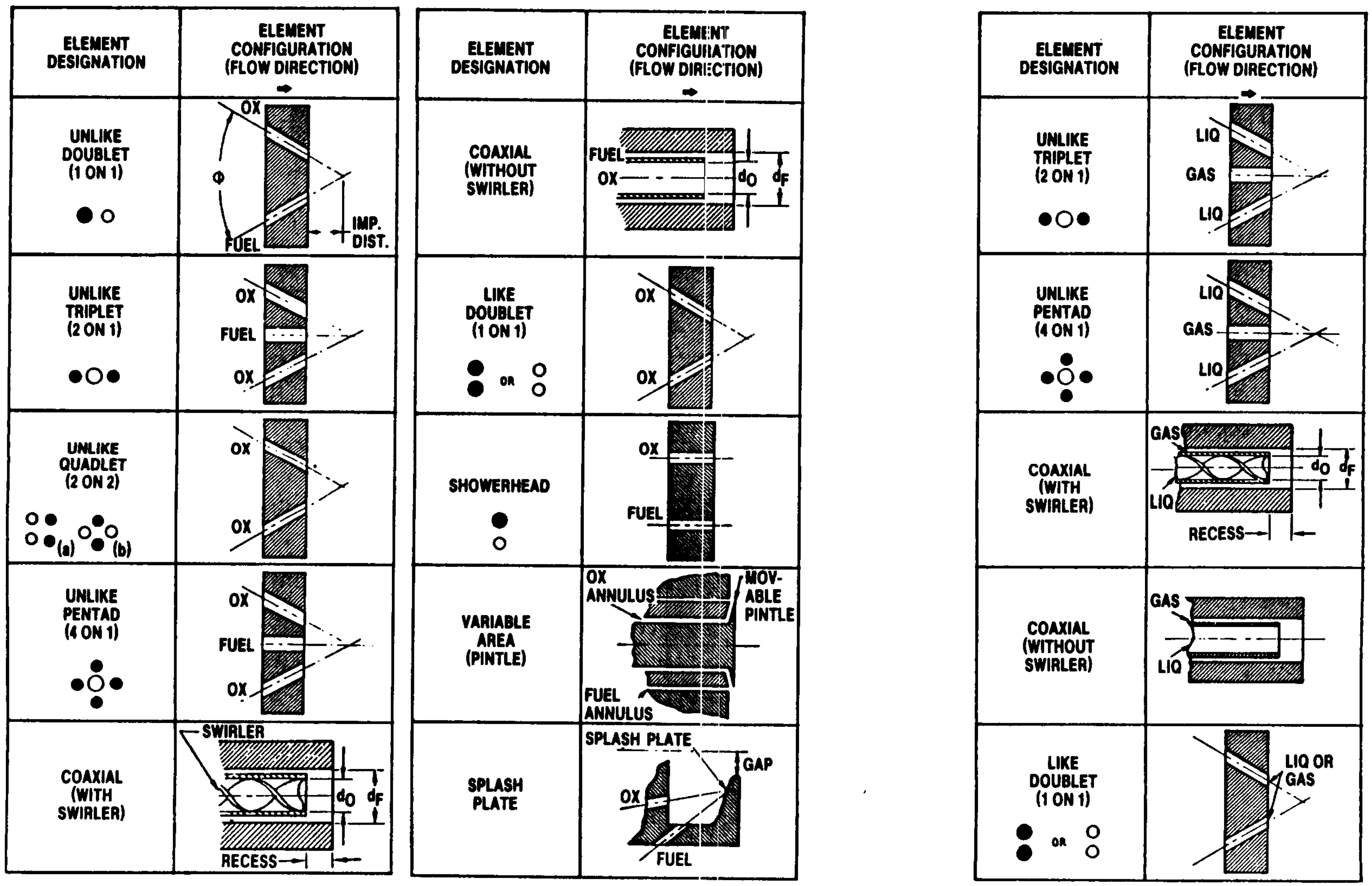
CANDIDATE INJECTOR ELEMENTS

THIS CHART PRESENTS A LIST OF CANDIDATE MAIN INJECTOR ELEMENTS SUBJECTED TO INITIAL SCREENING FOR THE STBE. THE ELEMENTS ARE DIVIDED INTO LIQUID/LIQUID AND GAS/LIQUID CATEGORIES

CANDIDATE INJECTOR ELEMENTS

LIQUID/LIQUID

GAS/LIQUID



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INJECTOR ELEMENT SELECTION TRADES

THE KEY TRADE FACTORS OR CONSIDERATIONS USED FOR INJECTOR ELEMENT ASSESSMENT AND THE MAIN INJECTOR ELEMENT CANDIDATES ARE EVALUATED FOR BOTH LIQUID/LIQUID AND GAS/LIQUID PROPELLANT COMBINATIONS. EACH OF THESE INJECTOR ELEMENT TYPES WERE RATED ON A SCALE FROM 1 TO 3 (LOW TO HIGH) WITH REGARD TO POTENTIAL PERFORMANCE (ATOMIZATION, MIXING, AND THROTTLEABLE), STABILITY, COMPATIBILITY, PRODUCIBILITY, AND EXPERIENCE ADVANTAGES. THE ELEMENTS WITH THE HIGHEST COMBINED TOTALS ARE JUDGED TO BE THE BEST.

INJECTOR ELEMENT SELECTION TRADE STUDY

TRADE FACTOR	ELEMENT CONFIGURATIONS							
	LIKE DOUBLET		TRIPLET		UNLIKE DOUBLET		COAXIAL	
	LIQ/LIQ	GAS/LIQ	LIQ/LIQ	GAS/LIQ	LIQ/LIQ	GAS/LIQ	LIQ/LIQ	GAS/LIQ
ATOMIZATION	3	3	3	3	3	3	2	3
MIXING	2	1	3	2	3	2	2	3
THROTTLEABLE	3	TBD	2	2	2	TBD	TBD	2
STABILITY	3	2	2	TBD	2	TBD	TBD	3
COMPATIBILITY	3	3	2	2	2	2	3	3
PRODUCIBILITY	3	3	3	3	3	3	2	3
EXPERIENCE	3	1	3	2	3	1	1	3
TOTAL	20	13	18	14	18	11	10	20

3-HIGH 2-MEDIUM 1-LOW

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LIQUID/LIQUID INJECTOR ELEMENT SELECTION

THE LIKE DOUBLET ELEMENT IS SELECTED AS THE BASELINE FOR THE LIQUID/LIQUID INJECTOR CONCEPTS FOR FIVE ENGINES; #1, 2, 4, 5 & 6.

LIQUID/LIQUID INJECTOR ELEMENT SELECTION

- **ENGINE CONFIGURATION**
  - ENGINE 1 - LOX/RP-1
  - ENGINE 2 - LOX/PROPANE
  - ENGINE 4 - LOX/RP-1, H_2 COOLED
  - ENGINE 5 - LOX/PROPANE, H_2 COOLED
  - ENGINE 6 - LOX/METHANE, H_2 COOLED
- **ELEMENT SELECTION**
  - IMPINGING LIKE DOUBLET
    - PROVEN/EXPERIENCE
    - STABLE
    - PERFORMANCE
    - CHAMBER COMPATIBLE
    - PRODUCIBLE

86D-9-1926

GAS/LIQUID INJECTOR ELEMENT SELECTION

THE COAXIAL INJECTOR ELEMENT CONCEPT IS SELECTED AS THE BASELINE FOR ENGINE #3.

GAS/LIQUID INJECTOR ELEMENT SELECTION

- **ENGINE CONFIGURATION**
  - ENGINE 3 — LOX/METHANE
- **ELEMENT SELECTION**
  - COAXIAL
    - PROVEN/EXPERIENCE
    - STABLE
    - PERFORMANCE
    - CHAMBER COMPATIBILITY
    - PRODUCIBILITY

86D-9-1927

ELEMENT ARRANGEMENT REQUIREMENTS

ELEMENT ARRANGEMENT REQUIREMENTS ARE IDENTIFIED HERE. KEY ELEMENT PATTERN AND ELEMENT ORIENTATION CONSIDERATIONS ARE LISTED.

ELEMENT ARRANGEMENT REQUIREMENTS

- **PATTERN**
  - MASS FLUX UNIFORMTIY
  - MIXTURE RATIO UNIFORMITY
  - INTERELEMENT MIXING (IMPINGING)
- **ORIENTATION**
  - HEAT TRANSFER RATE
  - HARDWARE COMPATIBILITY
    - CHAMBER WALL
    - BAFFLES

ELEMENT ARRANGEMENT SELECTION

SELECTION OF THE ELEMENT ARRANGEMENTS FOR THE LIQUID/LIQUID AND THE GAS/LIQUID INJECTORS ARE PRESENTED. A "BOX" PATTERN IS SELECTED FOR THE LIKE DOUBLET LIQUID/LIQUID CONCEPTS AND A SYMMETRICAL PATTERN IS SELECTION FOR THE COAXIAL GAS/LIQUID CONCEPT. PRIMARY REASONS FOR THESE SELECTIONS ARE GIVEN.

ELEMENT ARRANGEMENT SELECTION

LIQUID/LIQUID

- **"BOX" PATTERN**
  - PERFORMANCE
    - ENHANCE ATOMIZATION
    - SIMULATES COAXIAL ELEMENT MIXING
  - STABILITY
    - LIKE DOUBLET MIXING
    - SIMULATES COAXIAL ELEMENT
  - CHAMBER WALL COMPATIBILITY

GAS/LIQUID

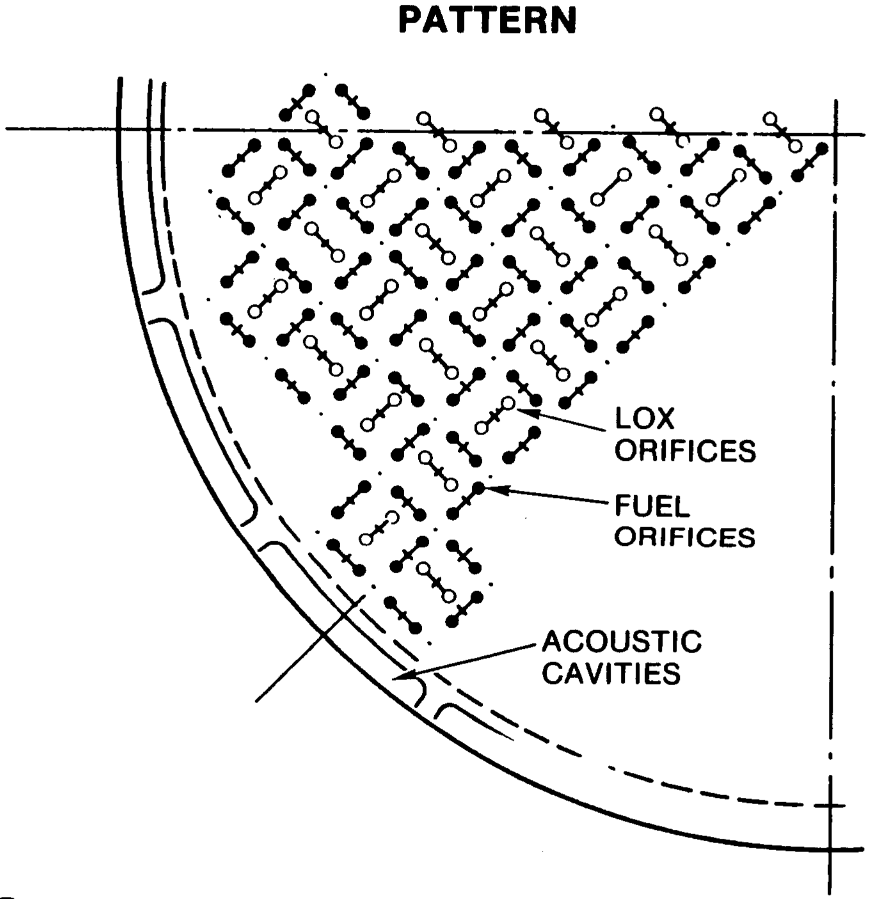
- **SYMMETRICAL PATTERN**
  - PERFORMANCE
    - UNIFORM MASS FLUX
    - UNIFORM MIXTURE RATIO
  - STABILITY
    - EXPERIENCE BASE
  - CHAMBER WALL COMPATIBILITY
    - FUEL RICH BOUNDARY

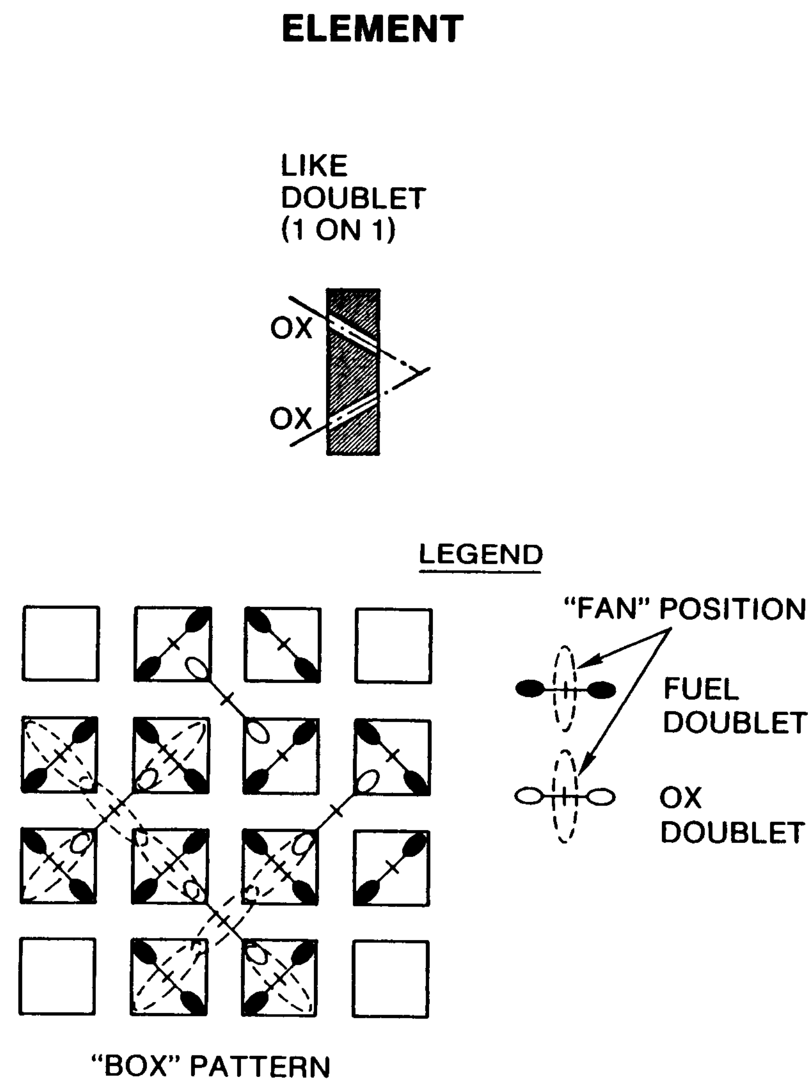
86D-9-1929

BASELINE LIQUID/LIQUID INJECTOR

THIS CHART GRAPHICALLY SHOWS THE LIKE DOUBLET INJECTOR ELEMENT AND THE BOX PATTERN ARRANGEMENT OF INJECTOR ELEMENTS FOR THE LIQUID/LIQUID INJECTOR CONCEPTS.

BASELINE LIQUID/LIQUID INJECTOR
ENGINES 1, 2, 4, 5, AND 6





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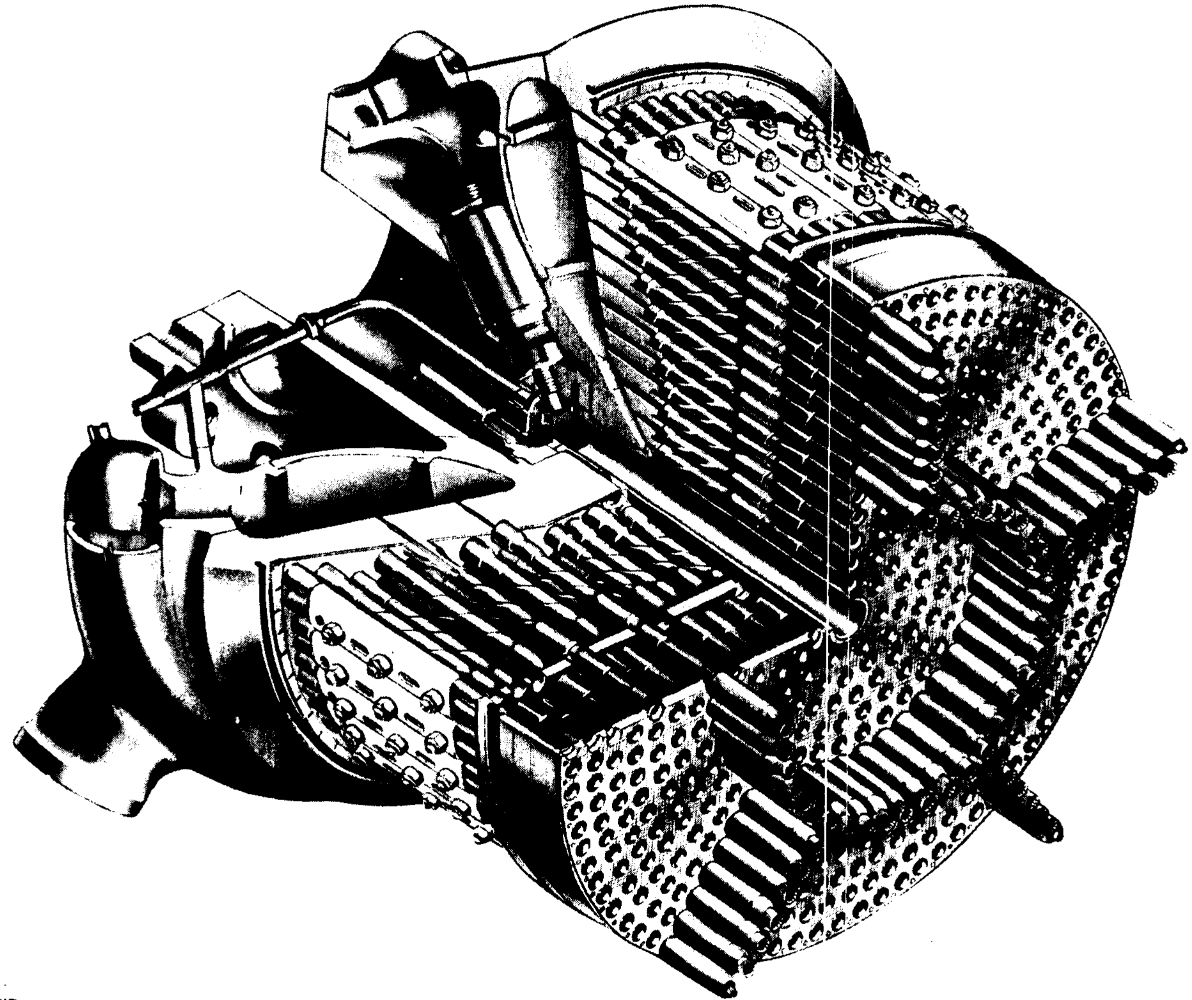
BASELINE GAS/LIQUID INJECTOR

THE GAS/LIQUID COAXIAL INJECTOR ELEMENT AND A TYPICAL SYMMETRICAL COAXIAL INJECTOR ELEMENT ARRANGEMENT ARE GRAPHICALLY SHOWN HERE.

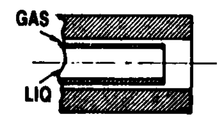
BASELINE GAS/LIQUID INJECTOR
ENGINE 3

PATTERN



ELEMENT

COAXIAL



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COMBUSTION STABILITY CONSIDERATIONS

PRIMARY COMBUSTION STABILITY CONSIDERATIONS FOR THIS STBE STUDY ARE PRIOR EXPERIENCE, OPERATING CONDITIONS OF THE CHAMBER, INJECTOR/COMBUSTOR GEOMETRY FEATURES AND STABILITY AIDS. KEY PARAMETERS ARE LISTED UNDER EACH OF THE MAIN CONSIDERATION TOPICS.

COMBUSTION STABILITY CONSIDERATIONS

- **EXPERIENCE**
- **OPERATING CONDITIONS**
  - PROPELLANTS/TEMPERATURE
  - CHAMBER PRESSURE
  - MR/MASS DISTRIBUTION
  - STREAM AND DROP SIZE/ATOMIZATION RATE/ CONCENTRATION
  - MIXING/BURNING RATE
- **GEOMETRY**
  - CHAMBER DIAMETER
  - CHAMBER LENGTH
  - INJECTION ELEMENT TYPE/SPACING/ORIENTATION
  - ELEMENT ORIFICE DIAMETER
- **STABILITY DEVICES**
  - BAFFLES — LENGTH
  - ABSORBERS/CAVITIES — OPEN AREA AND ORIENTATION
  - LINERS

COMBUSTION STABILITY ANALYSES

THIS CHART PRESENTS THE PRIMARY STABILITY THEORIES (TOOLS) USED TO ANALYZE COMBUSTION STABILITY. THE PRIEM ANALYSIS AND THE ROCKETDYNE STREAM BREAKUP CORRELATION WILL BE MAINLY USED FOR THE STBE STUDIES

COMBUSTION STABILITY ANALYSES

- **PRIEM**
  - RELATIVE STABILITY OF INJECTOR
  - ASSUMES DROPLET EVAPORATION CONTROLS
    - MODELS PHYSICAL EVAPORATION PROCESS
    - DEPENDS ON ACCURATE DROPLET SIZE DATA
- **SENSITIVE TIME LAG (N-TAU)**
  - STABILITY OF INJECTOR/CAVITY DESIGNS
    - WIDE APPLICATION
  - DETAILED CHAMBER ACOUSTIC TREATMENT
  - HUERISTIC COMBUSTION RESPONSE MODEL
    - MODEL IMPLIED FROM AVAILABLE STABILITY DATA
    - CSU EFFORT TO ANCHOR TO H-1 DATA
- **ROCKETDYNE STREAM BREAKUP CORRELATION**
  - STABILITY OF INJECTOR DESIGNS
    - FULL SIZE STABILITY DATA CORRELATION
  - ASSUMES STREAM BREAKUP CONTROLS
    - INCORPORATES STREAM BREAKUP PROCESS MODEL

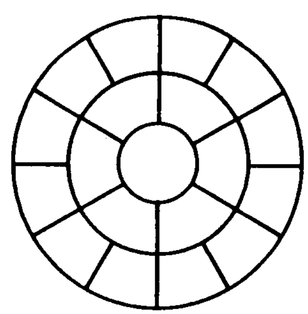
LIQUID/LIQUID INJECTOR STABILITY

STABILITY CONSIDERATIONS ARE IDENTIFIED FOR THE LIQUID/LIQUID INJECTORS. THE ELEMENT BY ITSELF, THE ELEMENT ARRANGEMENT, AND THE STABILITY AIDS ARE KEY TO ENHANCING STABILITY. BAFFLE/STABILITY AID SELECTION HAS NOT BEEN COMPLETED FOR THE BASELINE CONFIGURATION, HOWEVER, A 19 COMPARTMENT BAFFLE ARRANGEMENT IS TENTATIVELY SELECTED. AN ALTERNATE APPROACH IS TO DECREASE THE NUMBER OF COMPARTMENTS (BAFFLES).

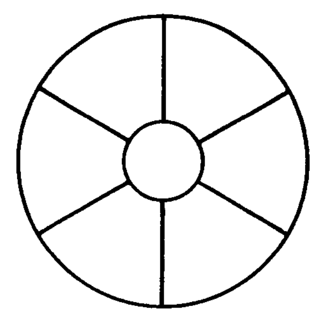
LIQUID/LIQUID INJECTOR STABILITY

- **STABILITY CONSIDERATIONS**
  - STABLE ELEMENT
  - "BOX" PATTERN WITH COAX COMBUSTION
  - BAFFLE CONFIGURATION
    - ACTIVE INJECTION BAFFLE
    - BIPROPELLANT COOLED BAFFLE
    - LENGTH

BASELINE



ALTERNATE



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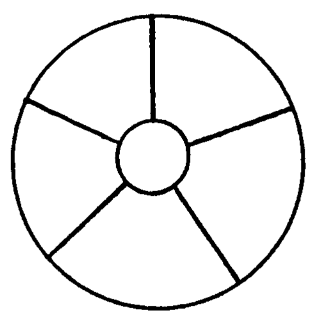
GAS/LIQUID INJECTOR STABILITY

KEY CONSIDERATIONS FOR ENSURING THE STABILITY OF THE GAS/LIQUID INJECTOR ARE THE LOX/H_2 AND LOX/CH_4 EXPERIENCES, THE STABLE COAXIAL INJECTOR ELEMENT ITSELF AND BAFFLES. TENTATIVELY THE BASELINE CONFIGURATION WILL UTILIZE A BAFFLE ARRANGEMENT SIMILAR TO THE SSME. THE ALTERNATE APPROACH WILL BE TO ELIMINATE THE BAFFLES

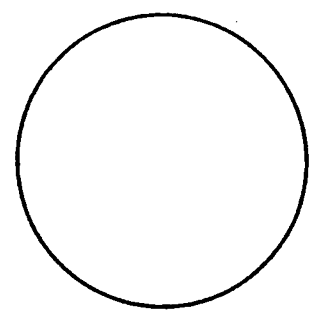
GAS/LIQUID INJECTOR STABILITY

- **STABILITY CONSIDERATIONS**
  - EXPERIENCE
  - STABLE COAXIAL ELEMENT
  - BAFFLE CONFIGURATION
    - ACTIVE INJECTION BAFFLE
    - BIPROPELLANT COOLANT BAFFLE

BASELINE



ALTERNATE (NO BAFFLES)



COMBUSTION CHAMBER AND NOZZLE

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COMBUSTION CHAMBER/NOZZLE DESIGN CONSIDERATIONS

PRIMARY COMBUSTION CHAMBER AND NOZZLE DESIGN CONSIDERATIONS ARE LISTED HERE. THE OPERATING CONDITIONS PLAY A MAJOR ROLE IN THE DESIGN. THE COOLANT FLOW CIRCUIT, THE TYPE OF COOLANT PASSAGES, THE COMBUSTOR GEOMETRY AND THE NOZZLE GEOMETRY ARE ALSO IMPORTANT DESIGN CONSIDERATIONS.

COMBUSTION CHAMBER/NOZZLE DESIGN CONSIDERATIONS

- **OPERATING CONDITIONS**
  - COOLANT TYPE AND FLOW
  - PRESSURES
  - HEAT LOADS
  - LIFE REQUIREMENTS
- **COOLANT FLOW CIRCUIT**
  - SINGLE PROPELLANT REGENERATIVE (SERIES OR PARALLEL)
  - DUAL PROPELLANT REGENERATIVE
  - FILM — BLC
- **CONFIGURATION**
  - COOLANT PASSAGES
    - CHANNEL
    - TUBES
  - COMBUSTOR CONTOUR
    - LENGTH
    - CONVERGENCE ANGLE
    - CONTRACTION RATIO
    - NOZZLE ATTACHMENT POINT
  - NOZZLE SIZING
    - SHAPE
    - LENGTH
    - EPSILON

CHAMBER/NOZZLE OPERATING CONDITIONS

THESE CHAMBER AND NOZZLE OPERATING CONDITIONS PLAY A MAJOR ROLE IN THE DESIGN. TYPE OF COOLANT, COOLANT DELTA-P AND COOLANT OUTLET TEMPERATURE ARE SOME OF THE MORE IMPORTANT PARAMETERS.

CHAMBER/NOZZLE OPERATING CONDITIONS

ENGINE CONFIGURATION NUMBER	1	2	3	4	5	6
COOLANT TYPE PROPELLANT	RP-1	C_3H_8	CH_4	H_2	H_2	H_2
CHAMBER CLNT FLOW, lb/s	382	339	303	31	32	39
P INLET, psi	6673	6050	5933	6062	6070	6122
ΔP, psi	3853	1706	1477	960	962	977
T INLET, °R	520	160	210	38	38	38
T OUTLET, °R	849	510	460	552	544	463
NOZZLE CLNT FLOW, lb/s	271	339	303	31	32	39
P INLET, psi	3468	4515	4604	5102	5108	5145
ΔP, psi	648	171	148	96	96	98
T INLET, °R	520	160	210	552	544	463
T OUTLET, °R	1139	711	608	1431	1409	1175

86D-9-1950

CHAMBER/NOZZLE GEOMETRY

BASELINE CHAMBER AND NOZZLE GEOMETRY ARE LISTED. CHAMBER DIAMETER AND LENGTH PARAMETERS CAN SIGNIFICANTLY EFFECT PERFORMANCE, STABILITY AND HEAT TRANSFER.

CHAMBER/NOZZLE GEOMETRY

ENGINE CONFIGURATION NUMBER	1	2	3	4	5	6
COOLANT TYPE PROPELLANT	RP-1	C_3H_8	CH_4	H_2	H_2	H_2
DIA THROAT, in.	15.4	12.6	12.4	11.4	11.3	11.3
DIA CHAMBER, in.	25.3	20.7	20.4	18.7	18.6	18.6
CONTRACTION RATIO	2.7	2.7	2.7	2.7	2.7	2.7
L CHAMBER, in.	16.9	14.4	14.2	13.2	13.2	13.2
EPSILON, NOZZLE ATTACH	7.0	7.0	7.0	7.0	7.0	7.0
L NOZZLE, in.	123.2	119.5	117.9	117.0	117.0	116.0
EPSILON, NOZZLE	42.9	56.9	57.1	64.3	64.9	64.6

86D-9-1939

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COMBUSTION CHAMBER/NOZZLE DESIGN GROUNDRULES

THIS TABLE PRESENTS THE GROUNDRULES AND CONSTRAINTS THAT HAVE BEEN SELECTED AND INCORPORATED INTO THE ENGINE BALANCE PROGRAM. THE PRIMARY ADVANTAGE OR REASONS FOR THESE GROUNDRULES ARE ALSO PRESENTED.

COMBUSTION CHAMBER/NOZZLE DESIGN GROUNDRULES

COMPONENT	GROUNDRULE	ADVANTAGE
COOLANT JACKET	COOLANT BULK TEMP LIMIT (°R) • RP-1 — 1060-1200 • C_3H_8 — 1320 • CH_4 — 1760	AVOID COKING
	HOT GAS WALL TEMP LIMIT (°R) — 1560	LIFE
COMBUSTION CHAMBER	COOLANT PASSAGE MATERIAL — COPPER ALLOY	HEAT TRANSFER
	COOLANT PASSAGE GEOMETRY • CHANNELS — SLOTTED • DEPTH/WIDTH — ≤5	HEAT TRANSFER FABRICATION
	CONTOUR GEOMETRY • CYLINDRICAL LENGTH — 3 in • CONVERGENCE ANGLE — 25.4 deg • CONTRACTION RATIO — 2.7 • EXPANSION RATIO — 7.0	PERFORMANCE
NOZZLE	COOLANT PASSAGE MATERIAL — A286	HIGH STRENGTH, COMPATIBILITY
	COOLANT PASSAGE GEOMETRY — TUBE	WEIGHT
	CONTOUR GEOMETRY • LENGTH — 80% BELL • EXIT PRESSURE — 6 psia (ODE)	PERFORMANCE, WEIGHT PERFORMANCE

86D-9-1998:

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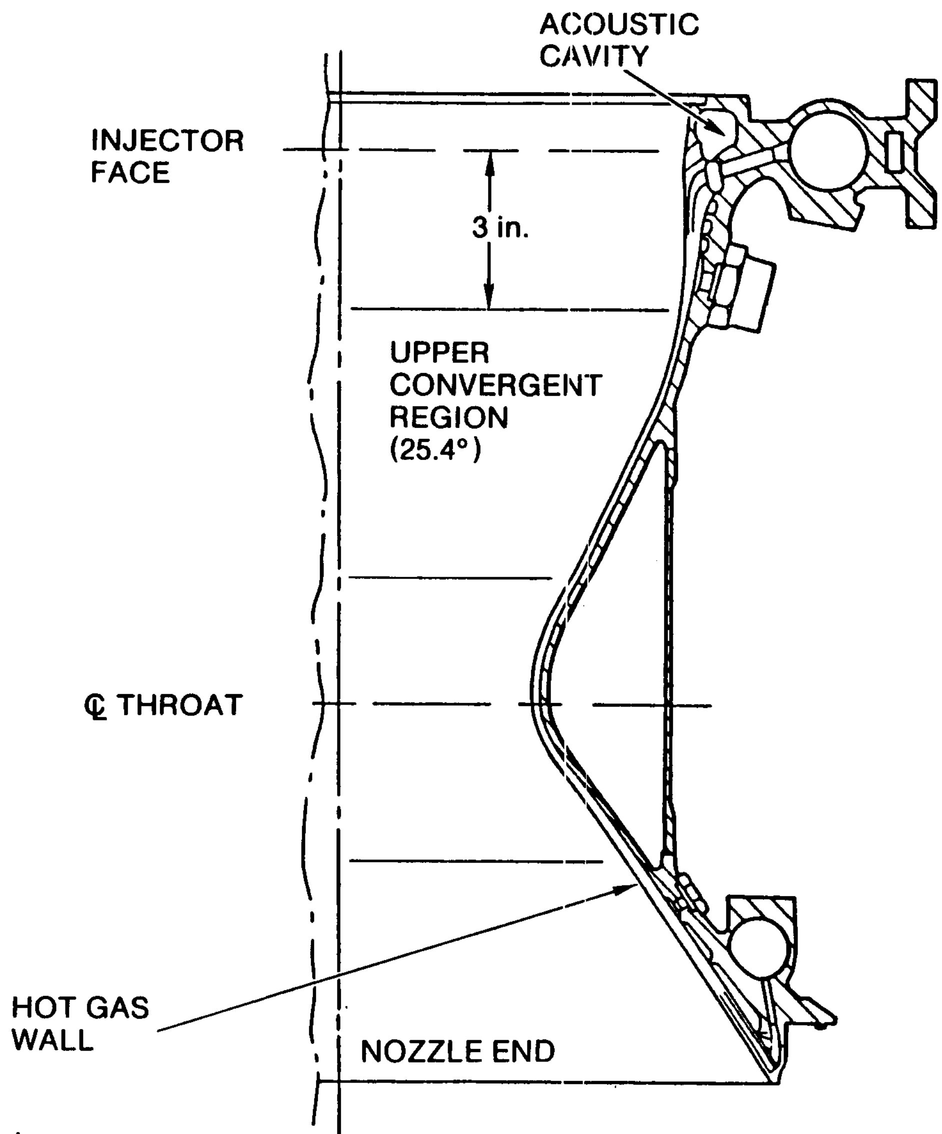
TYPICAL MAIN COMBUSTION CHAMBER

THIS IS A TYPICAL MAIN COMBUSTION CHAMBER CANDIDATE WITH CHANNEL WALL CONSTRUCTION.

C-3

TYPICAL MAIN COMBUSTION CHAMBER

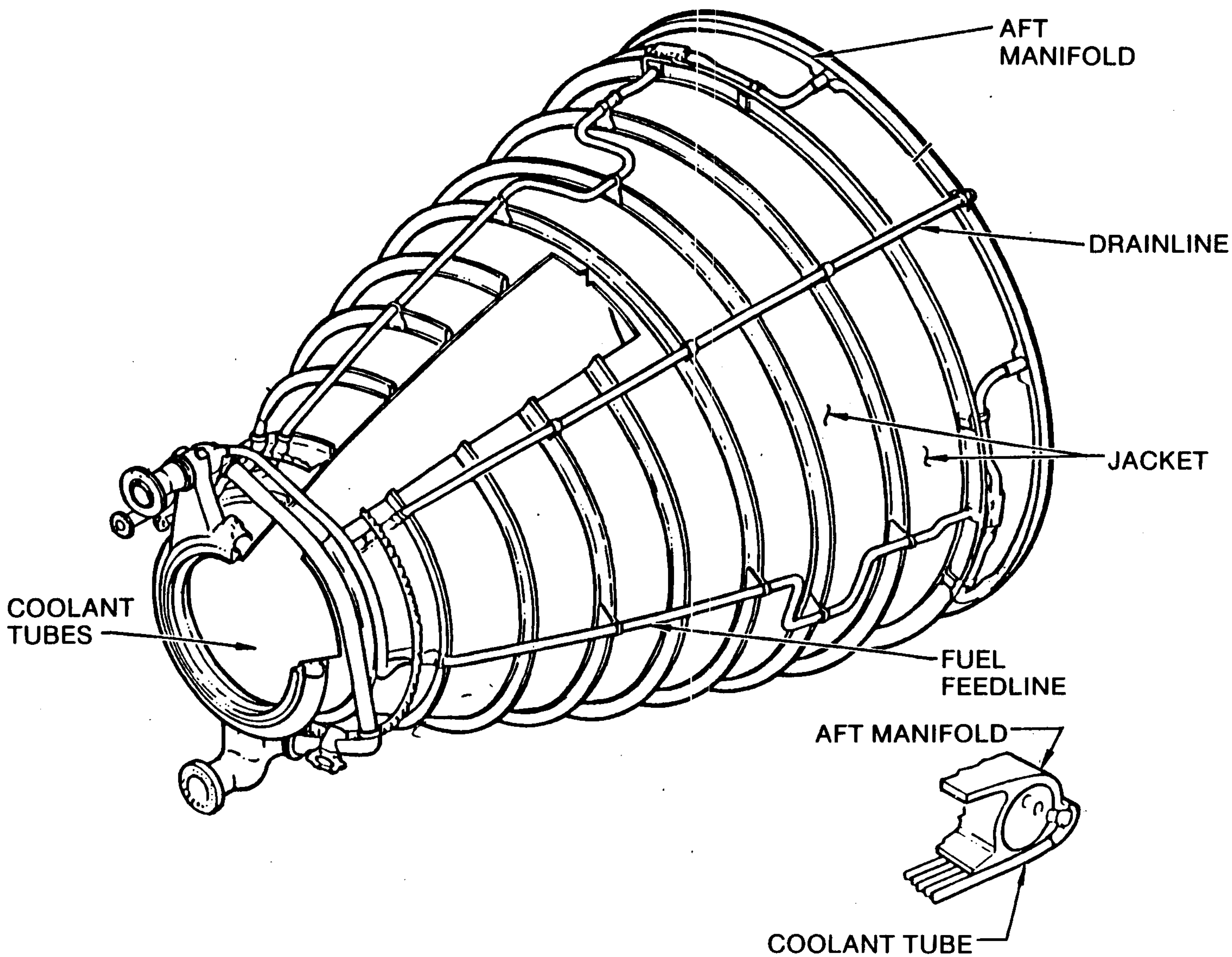


86D-9-1942

TYPICAL NOZZLE

THIS FIGURE SHOWS A TYPICAL CHAMBER NOZZLE USING COOLANT TUBES.

TYPICAL NOZZLE

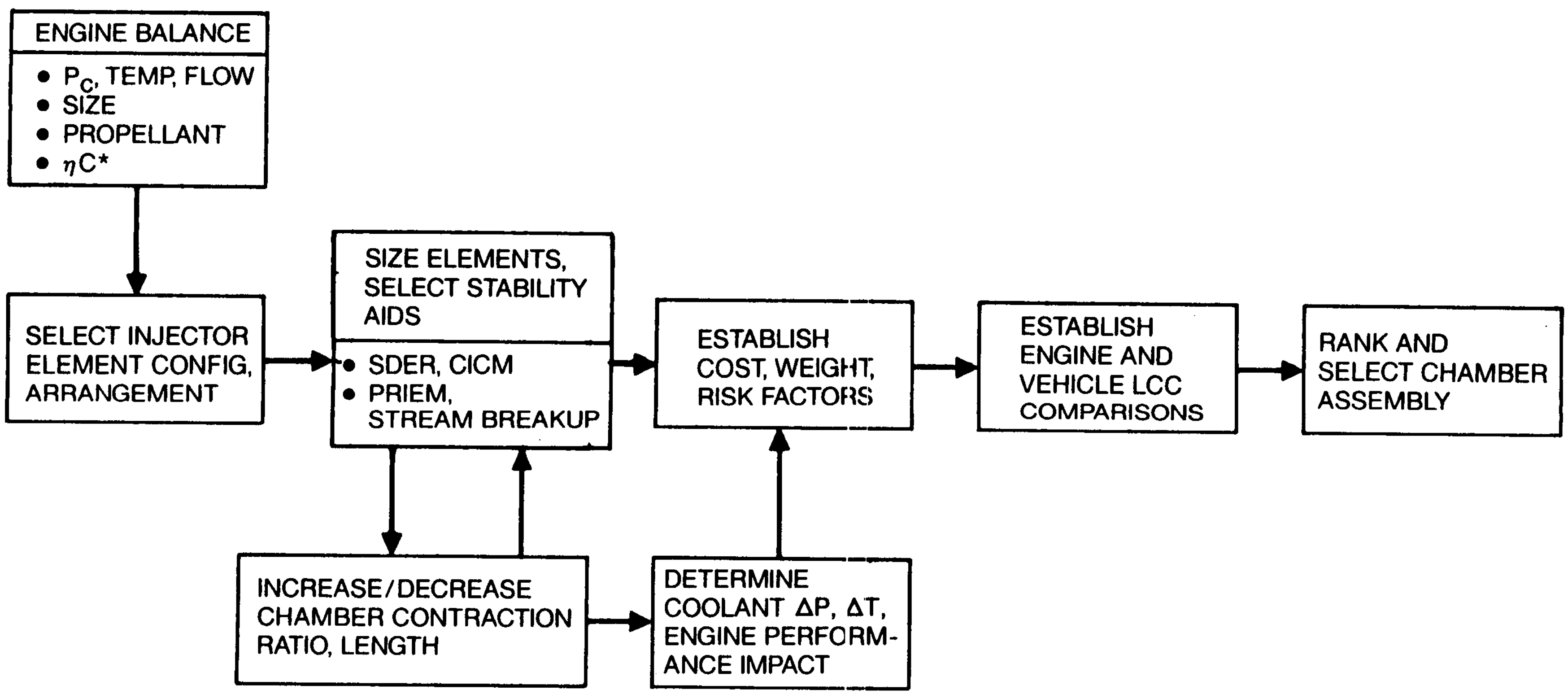


86D-9-1943

CHAMBER ASSEMBLY TRADE STUDIES

CHAMBER ASSEMBLY TRADE STUDIES TO BE CONDUCTED ARE DIAGRAMMED HERE. THE FIRST TWO STEPS HAVE BEEN ACCOMPLISHED. THE NEXT STEP IS TO SELECT THE INJECTOR ELEMENT SIZES AND STABILITY AIDS USING THE BASELINE CHAMBER SIZE. COST, WEIGHT AND RISK FACTORS ARE THEN ESTABLISHED FOR THIS BASELINE INJECTOR AND CHAMBER. THE NEXT STEP IS TO CHANGE THE CHAMBER GEOMETRY; ESTABLISH NEW INJECTOR SIZES AND STABILITY AIDS; DETERMINE ENGINE IMPACT; ESTABLISH NEW COST, WEIGHT AND RISK VALUES OR "DELTAS"; AND THEN ESTABLISH ENGINE AND VEHICLE LCC COMPARISONS. THESE COMPARISONS ARE THEN USED TO HELP SELECT THE OPTIMUM CHAMBER ASSEMBLY FOR EACH ENGINE AND TO HELP SELECT THE BEST ENGINE CONCEPT.

CHAMBER/INJECTOR ASSEMBLY TRADE STUDY



86D-9-1997:

CHAMBER ASSEMBLY TRADE STUDY RESULTS

THE CHAMBER ASSEMBLY TRADE STUDY RESULTS WILL BE FORMATTED AS SHOWN BY THIS TABLE. CHAMBER ASSEMBLY COST, WEIGHT, AND RISK IMPACTS WILL BE ASSESSED AS WELL AS ENGINE AND VEHICLE LIFE CYCLE COSTS.

CHAMBER/INJECTOR ASSEMBLY TRADE STUDY
RESULTS

ENGINE	BASELINE			NEW			LCC ANALYSIS				
	D_O/D_F	ϵ_C/L	STABILITY AIDS	D_O/D_F	ϵ_C/L	STABILITY AIDS	$\Delta\$$	ΔW_T	ΔRISK	ΔLCC_{ENG}	ΔLCC_{VEH}
1		2.7/16.9									
2		2.7/14.4									
3		2.7/14.2									
4		2.7/13.2									
5		2.7/13.2									
6		2.7/13.2									
11		2.7/14.4									
12		2.7/13.6									
18		2.7/11.2									

86D-9-1996

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GAS GENERATOR

GAS GENERATOR INJECTOR DESIGN CONSIDERATIONS

KEY GG INJECTOR DESIGN CONSIDERATIONS ARE LISTED; NAMELY THE OPERATING CONDITIONS, INJECTION ELEMENT/ARRANGEMENT SELECTION, COMBUSTION STABILITY, AND COMBUSTOR SIZE.

GAS GENERATOR INJECTOR DESIGN CONSIDERATIONS

- OPERATING CONDITIONS
- INJECTION ELEMENT/ARRANGEMENT SELECTION
- COMBUSTOR SIZING
- COMBUSTION STABILITY

86D-9-1946

GAS GENERATOR OPERATING CONDITIONS

THESE PARAMETERS ARE THE PRIMARY GG OPERATING CONDITIONS FOR THE SIX STBE (1995 IOC) ENGINES. TYPE OF FUEL, OPERATING CHAMBER PRESSURE, FUEL INJECTION STATE, AND HOT GAS TEMPERATURE REQUIREMENTS ARE SOME OF THE MORE SIGNIFICANT ITEMS FOR THIS STUDY.

GAS GENERATOR OPERATING CONDITIONS

ENGINE CONFIGURATION NUMBER	1	2	3	4	5	6
T/C PROPELLANT COMBINATION	LOX/RP-1	LOX/C_3H_8	LOX/CH_4	LOX/RP-1	LOX/C_3H_8	LOX/CH_4
G.G. FUEL PROPELLANT	RP-1	C_3H_8	CH_4	H_2	H_2	H_2
G.G. OXIDIZER PROPELLANT	O_2	O_2	O_2	O_2	O_2	O_2
Pc, psia	2349	3407	3495	4165	4170	4200
W Ox, lb/s	46	29	38	10	10	18
W Fl, lb/s	111	105	95	31	32	39
MR, O/F	0.41	0.27	0.40	0.30	0.32	0.46
P INJ Ox, psia	2820	4089	4194	4998	5004	5040
T INJ Ox, °R	163	163	163	163	163	163
P INJ Fl, psia	2820	4089	4194	4998	5004	5040
T INJ Fl, °R	520	611	534	1431	1409	1175
FUEL INJ STATE	LIQ	LIQ	GAS	GAS	GAS	GAS
EXHAUST TEMP, °R	2000	2000	2000	2000	2000	2000

86D-9-1947

GAS GENERATOR INJECTION ELEMENT SELECTION

THIS CHART PRESENTS THE TYPE OF INJECTION ELEMENT SELECTED AS BASELINE FOR EACH OF THE 6 ENGINES. A LIKE IMPINGING DOUBLET IS SHOWN FOR THE TWO LIQUID/LIQUID GG INJECTORS AND A COAXIAL ELEMENT SELECTED FOR THE GAS/LIQUID INJECTORS.

GAS GENERATOR INJECTION ELEMENT SELECTION

ENGINE NUMBER	MAIN FUEL	NOZZLE/ CHAMBER COOLANT	GG FUEL	PROPELLANT INJECTION PHYSICAL STATE	GG INJECTOR ELEMENT TYPE
1	RP-1	RP-1	RP-1	LIQ/LIQ	LIKE IMP
2	C_3H_8	C_3H_8	C_3H_8	LIQ/LIQ	LIKE IMP
3	CH_4	CH_4	CH_4	LIQ/GAS	COAX
4	RP-1	H_2	H_2	LIQ/GAS	COAX
5	C_3H_8	H_2	H_2	LIQ/GAS	COAX
6	CH_4	H_2	H_2	LIQ/GAS	COAX

86D-9-1948

BASELINE ELEMENT SELECTION RATIONALE

RATIONAL FOR SELECTING THE BASELINE GG INJECTOR ELEMENTS ARE PRESENTED. THE LIKE DOUBLETS ARE SELECTED BECAUSE OF FAVORABLE PRIOR EXPERIENCE, WALL COMPATIBILITY, GOOD STABILITY HISTORY, AND POTENTIALLY GOOD ATOMIZATION AND MIXING. THE COAXIAL ELEMENTS ARE SELECTED FOR BASICALLY THE SAME REASONS BUT WITH GAS/LIQUID PROPELLANTS.

BASELINE GG ELEMENT SELECTION
RATIONALE

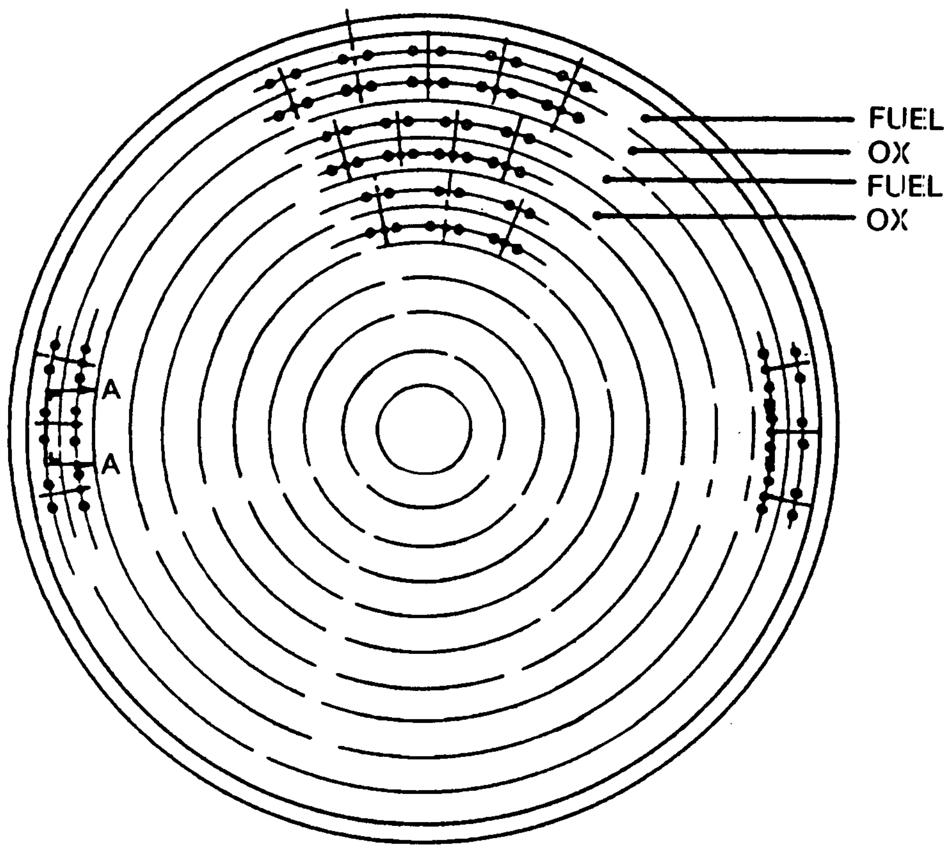
- **LIKE DOUBLETS — LIQUID/LIQUID**
  - EXPERIENCE
  - GOOD WALL COMPATIBILITY
  - STABILITY
  - GOOD ATOMIZATION AND MIXING CAN BE ACHIEVED WITH SIZING AND FAN ORIENTATION
- **COAXIAL — GAS/LIQUID**
  - EXPERIENCE
  - VERY GOOD WALL CAPABILITY
  - STABILITY
  - ATOMIZATION AND MIXING VERY GOOD WITH HIGH ΔV AND SMALL ELEMENTS

LIQUID/LIQUID GG INJECTOR BASELINE PATTERN

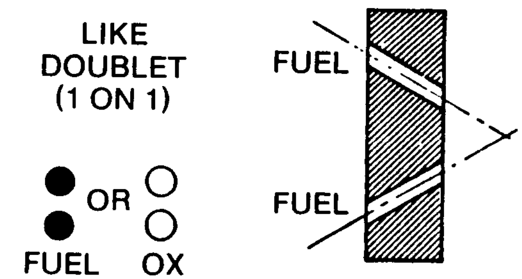
THE LIKE DOUBLE ELEMENT AND A TYPICAL ELEMENT ARRANGEMENT ARE SHOWN BY THESE SKETCHES.

LIQUID/LIQUID GG INJECTOR BASELINE PATTERN
ENGINES 1 AND 2

PATTERN



ELEMENT



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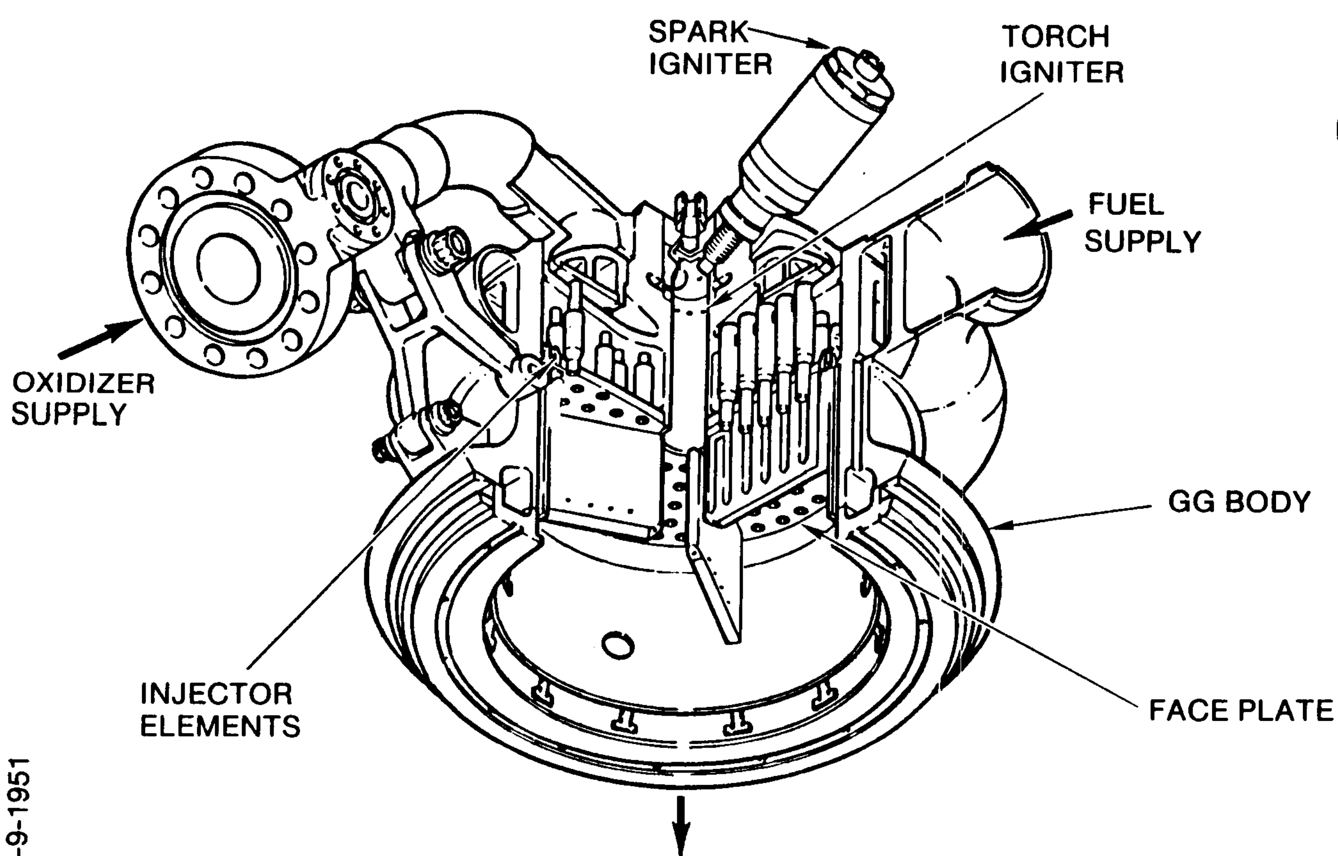
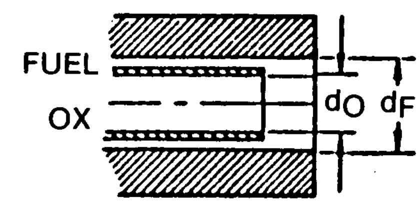
GAS/LIQUID GG INJECTOR BASELINE PATTERN

THE COAXIAL ELEMENT AND A TYPICAL COAXIAL ELEMENT ARRANGEMENT ARE PICTURED FOR THE GAS/LIQUID GG INJECTORS.

GAS/LIQUID GG INJECTOR BASELINE PATTERN
ENGINES 3, 4, 5, AND 6





86D-9-1951

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GAS GENERATOR COMBUSTOR DESIGN CONSIDERATIONS

PRIMARY GG COMBUSTOR DESIGN CONSIDERATIONS ARE PRESENTED FOR THE STBE STUDY. THESE INCLUDE THE OPERATING REQUIREMENTS AND CONFIGURATION FEATURES SUCH AS SIZE, SHAPE, AND MIXING ENHANCEMENT FEATURES TO OBTAIN A UNIFORM GAS TEMPERATURE

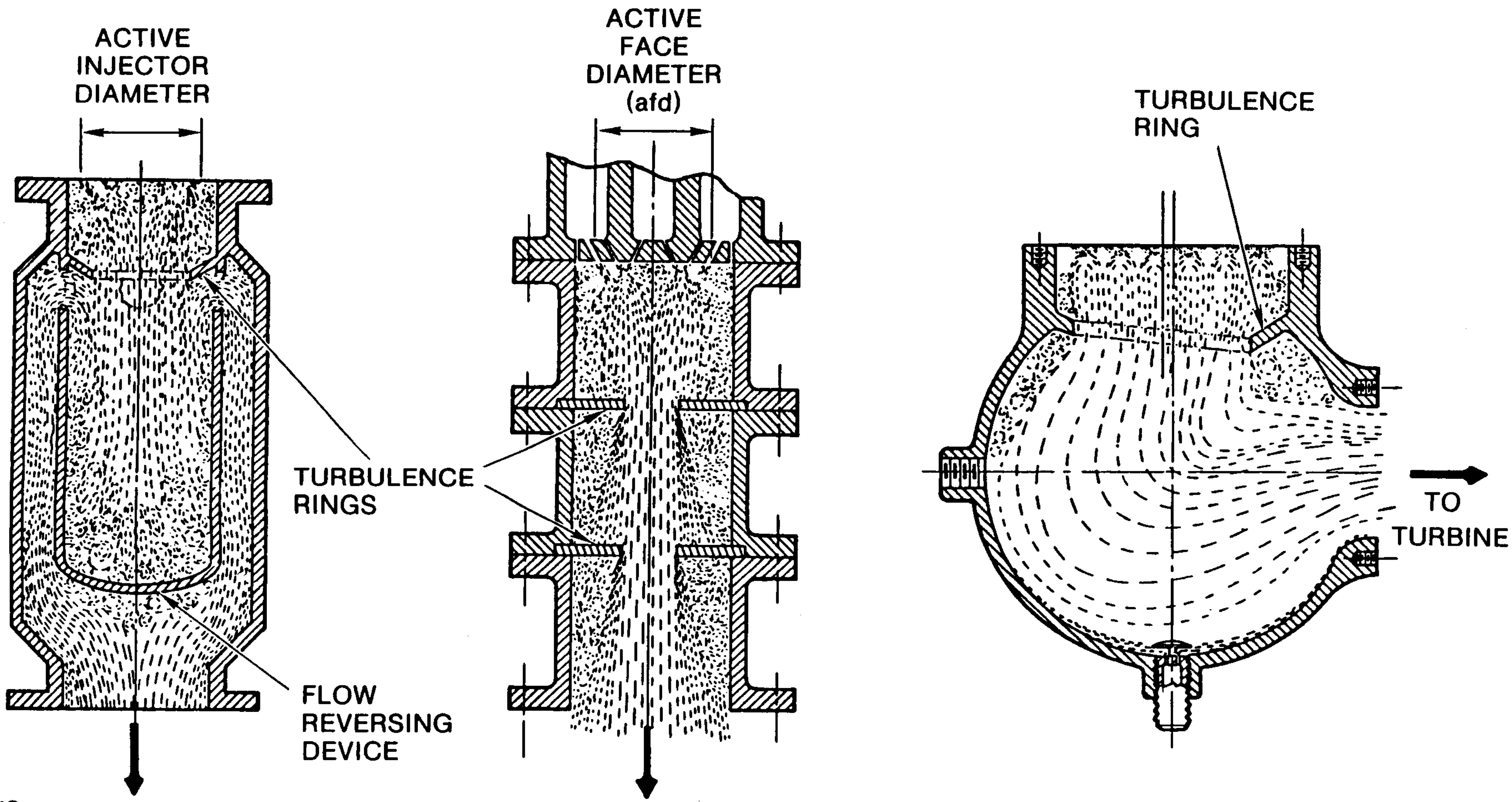
GAS GENERATOR COMBUSTOR DESIGN CONSIDERATIONS

- **OPERATING REQUIREMENTS**
  - FACILITATE ATOMIZATION BY CONTROLLING VELOCITIES
  - FORCE MIXING OF FUEL RICH PROPELLANTS
  - DELIVER UNIFORM HOT-GAS (COMPLETE COMBUSTION) TO TURBINE
  - INTERFACE WITH TURBINE
- **CONFIGURATION**
  - SHAPE — MAXIMIZE MIXING/MINIMIZE HOT SPOTS
    - AXIAL FLOW
    - REVERSE FLOW
    - AXIAL/SIDE OUTLET
  - SIZE — ALLOW FOR COMPLETE COMBUSTION
    - LENGTH/VOLUME — STAY TIME
    - DIAMETER — INJECTION ELEMENT PATTERN
  - MIXING ENHANCEMENT DEVICES
    - TURBULENCE RING
    - FLOW DIRECTION CHANGE

CANDIDATE GAS GENERATOR COMBUSTORS

SOME TYPICAL GAS GENERATOR COMBUSTORS ARE SHOWN. THE ACTUAL COMBUSTOR SELECTION WILL BE ACCOMPLISHED AFTER THE TURBINE AND ENGINE INTERFACES HAVE BEEN DEFINED.

CANDIDATE GAS GENERATOR COMBUSTORS



86D-9-1955

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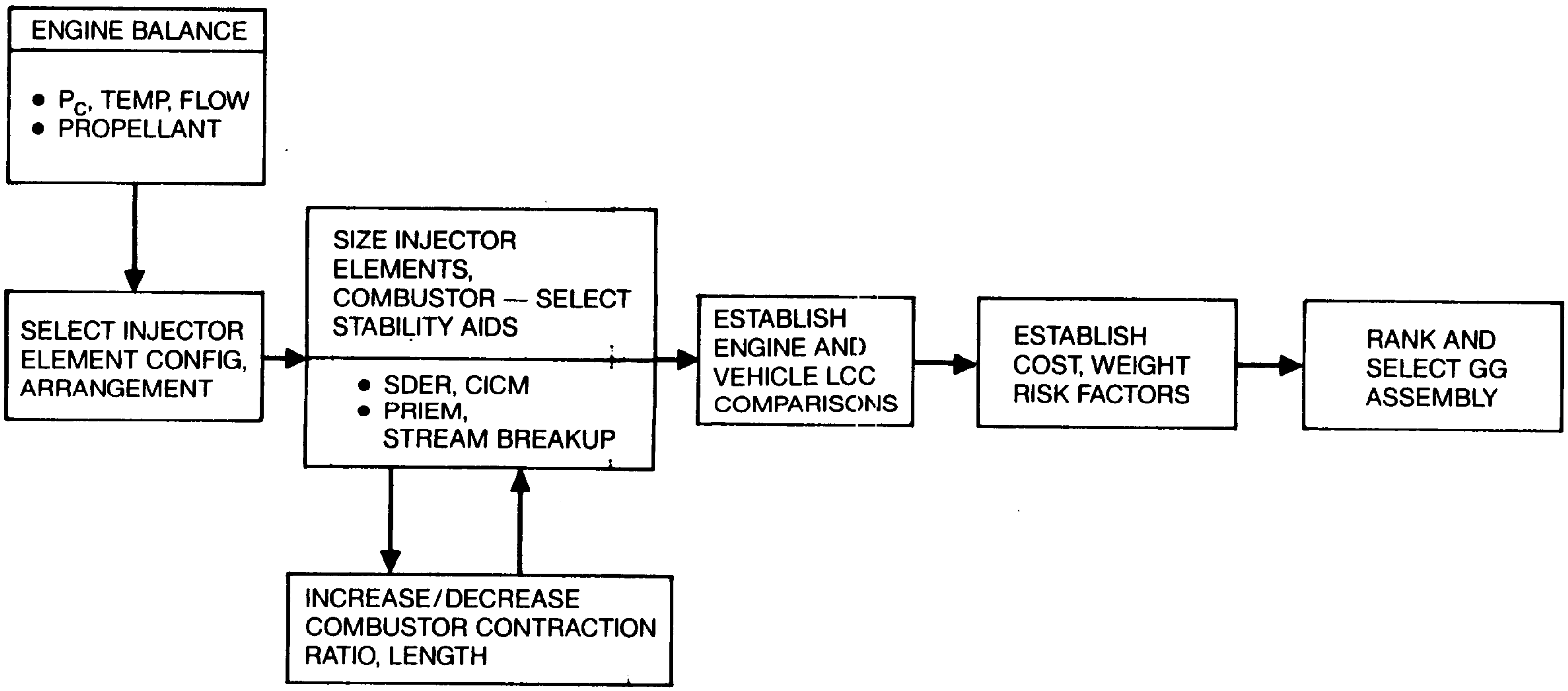
GAS GENERATOR ASSEMBLY TRADE STUDIES

THIS FLOW DIAGRAM SHOWS THE SEQUENCE OF EVENTS TO BE USED DURING THE GAS GENERATOR ASSEMBLY TRADE STUDIES. INJECTOR ELEMENT TYPE AND ARRANGEMENT HAVE BEEN COMPLETED. INJECTOR ELEMENT SIZES, COMBUSTOR SIZES, AND STABILITY AIDS ARE ESTABLISHED NEXT. THE TRADEOFF IS TO VARY THE COMBUSTOR SIZES AND THE INJECTOR ELEMENT SIZES TO OPTIMIZE THE ASSEMBLY. COST, WEIGHT, AND RISK FACTORS ARE ASSESSED RELATIVE TO THE COMBUSTOR/INJECTOR SIZE CHANGES. ALSO, ENGINE AND VEHICLE LIFE CYCLE COSTS ARE COMPARED. THE END RESULTS WILL BE TO SELECT THE OPTIMUM GG ASSEMBLY FOR EACH ENGINE CONFIGURATION.

GAS GENERATOR ASSEMBLY TRADE STUDY



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PM-80

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IGNITION SYSTEMS

86D-9-1957

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IGNITION SYSTEMS CONSIDERED

A LIST OF 6 CANDIDATE IGNITION SYSTEMS WERE SELECTED FOR STBE CONSIDERATION AS FOLLOWS.

IGNITION SYSTEMS CONSIDERED

- HYPERGOLIC FUEL
- SPARK TORCH
- PYROTECHNIC
- DIRECT SPARK
- COMBUSTION WAVE
- HYPERGOLIC OXIDIZER

IGNITION SYSTEM TRADE FACTORS

KEY TRADE FACTORS THAT WERE USED FOR THE IGNITION SYSTEM STUDIES ARE LISTED ON THIS CHART.

IGNITION SYSTEM TRADE FACTORS

- DEVELOPMENT MATURITY
- COST
- WEIGHT
- EXTERNAL POWER
- COMPLEXITY
- RELIABILITY
- HEALTH MONITORING (IGNITION DETECT)
- SAFETY

MAIN CHAMBER IGNITION SYSTEM SELECTION

THE FOLLOWING CHART PRESENTS THE MAIN CHAMBER IGNITION SYSTEM STUDY CONCLUSIONS FOR THE CANDIDATE ENGINE CONCEPTS. THE CONCLUSIONS ARE PRESENTED RELATIVE TO EACH OF THE TRADE FACTORS. LOX/C_3H_8 AND LOX/CH_4 FOR ENGINES 2, 5 & 6 WERE ASSUMED TO BE SIMILAR TO LOX/RP-1. AS A RESULT OF THIS STUDY IT WAS CONCLUDED THAT A HYPERGOLIC FUEL SYSTEM IS BEST FOR THE LOX/RP-1, LOX/C_3H_8, AND LOX/CH_4 MAIN CHAMBERS FOR ENGINE #1, 2, 4, 5 & 6. A SPARK TORCH SYSTEM BEST FOR THE LOX/CH_4 MAIN CHAMBER FOR ENGINE #3.

MAIN CHAMBER IGNITION SYSTEM SELECTION

	ENGINES 1 AND 4 LOX/RP-1	ENGINE 2 LOX/C_3H_8	ENGINE 3 LOX/CH_4	ENGINES 5 AND 6 LOX/C_3H_8 & $LOX\ CH_4$
RECOMMENDED SYSTEM	HYPERGOLIC FUEL	HYPERGOLIC FUEL	SPARK TORCH	HYPERGOLIC FUEL
DEV. MATURITY	DEVELOPED	*	EXP.	*
COST	LOW	LOW	MODERATE	LOW
WEIGHT	LOW	LOW	MODERATE	LOW
EXT. POWER	PRES. FUEL	PRES. FUEL	MINIMAL	PRES. GN_2
COMPLEXITY	LOW	LOW	LOW	LOW
HEALTH MONITORING	DETECTOR SWITCH	DETECTOR SWITCH	EX. MONITOR	DETECTOR SWITCH
SAFETY	EX. RECORD	TBD*	INHERENT	TBD*
RELIABILITY	HIGH	TBD*	TBD*	TBD*

*LOX/C_3H_8 AND LOX/CH_4 IGNITION FOR ENGINES 2, 5 AND 6 ASSUMED TO BE SIMILAR TO LOX/RP-1 AND LOX/CH_4 IGNITION FOR ENGINE 3 ASSUMED TO BE SIMILAR TO LOX/H_2

HYPERGOLIC FUEL BEST IF MULTIPLE IGNITION SOURCES REQUIRED AND/OR IF SIMPLE HYPERGOL SYSTEM CAN BE DEVELOPED TO WORK WITH CRYOGENIC FUELS (C_3H_8 AND CH_4)

GAS GENERATOR IGNITION SYSTEM SELECTION

THIS CHART PRESENTS THE GAS GENERATOR IGNITION SYSTEM STUDY CONCLUSIONS RELATIVE TO EACH OF THE TRADE FACTORS. CONCLUSIONS FROM THESE STUDIES SUGGESTS THAT PYROTECHNIC IGNITION IS BEST FOR ENGINES #1 and 2 AND SPARK TORCH BEST FOR ENGINES #3 - 6.

GAS GENERATOR IGNITION SYSTEM SELECTION

	ENGINE 1 LOX/RP-1	ENGINE 2 LOX/C_3H_8	ENGINE 3 LOX/CH_4	ENGINES 4, 5 AND 6 LOX/H_2
RECOMMENDED SYSTEM	PYROTECHNIC	PYROTECHNIC	SPARK TORCH	SPARK TORCH
DEV. MATURITY	DEVELOPED	TBD*	EXP.	DEVELOPED
COST	MODERATE	MODERATE	MODERATE	MODERATE
WEIGHT	LOW	LOW	MODERATE	MODERATE
EXT. POWER	MINIMAL	MINIMAL	MINIMAL	MINIMAL
COMPLEXITY	LOW	LOW	LOW	LOW
HEALTH MONITORING	LINK BREAK	LINK BREAK	EX. MONITOR	EX. MONITOR
SAFETY	EX. RECORD	TBD*	INHERENT	INHERENT
RELIABILITY	HIGH	TBD*	TBD*	HIGH

*LOX/C_3H_8 GG IGNITION ASSUMED TO BE SIMILAR TO LOX/RP-1, LOX/CH_4 GG IGNITION ASSUMED TO BE SIMILAR TO LOX/H_2

86D-9-1961

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STBE CONFIGURATION STUDY
SECOND QUARTERLY REVIEW
AGENDA

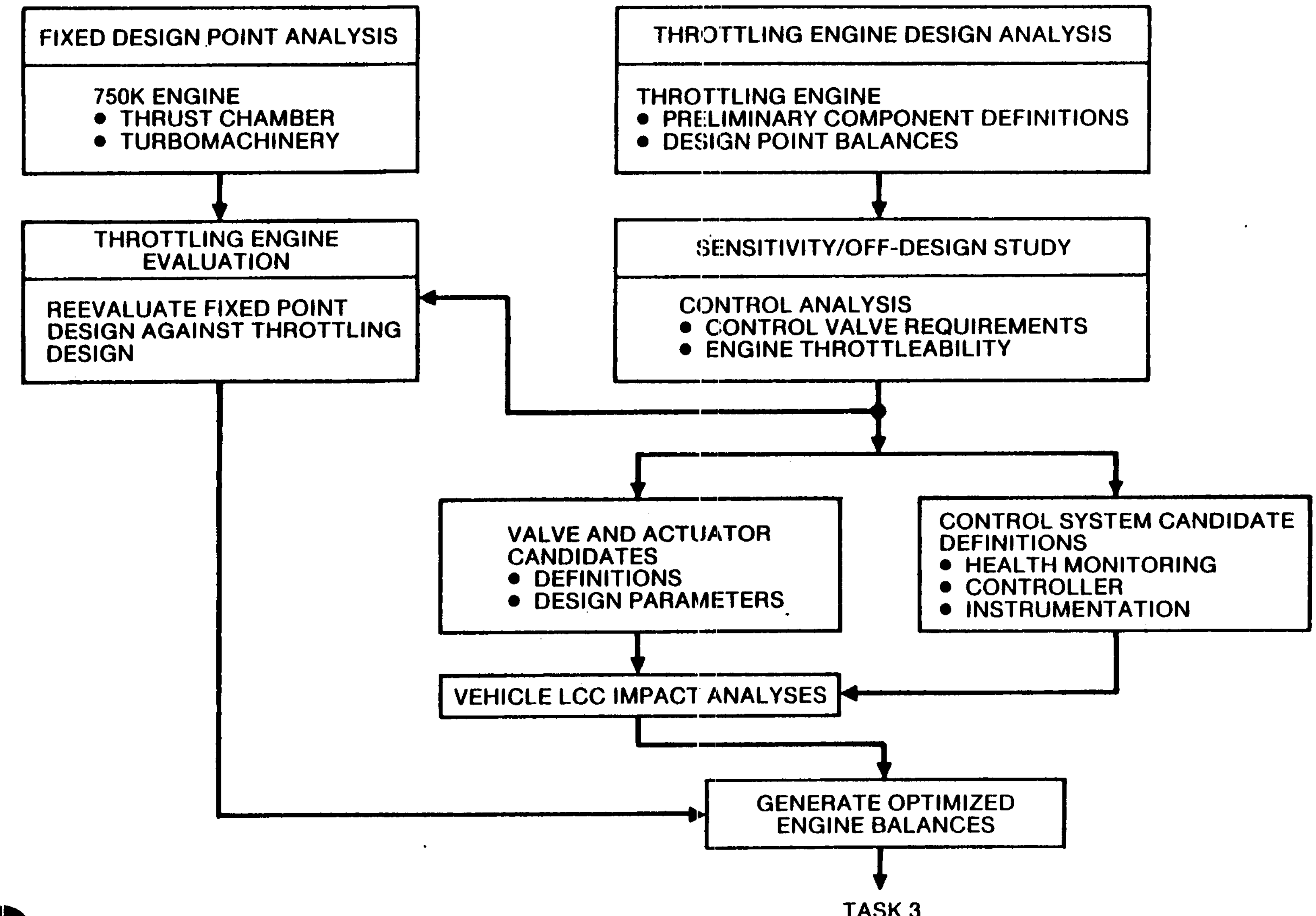
- INTRODUCTION .... F. KIRBY
- TASK 1 SUMMARY .... A. WEISS
- TASK 2 STATUS REVIEW
  - SUBSYSTEM OPTIMIZATION APPROACH .... A. WEISS
  - TURBOMACHINERY STUDIES .... A. EASTLAND
  - COMBUSTION DEVICES STUDIES .... P. MEHEGAN
  - THROTTLING ON-DESIGN/OFF-DESIGN STUDY .... W. BISSELL, D. NGUYEN
  - CONTROL SYSTEM AND HEALTH MONITOR STUDIES .... R. BREWSTER
- SUMMARY .... A. WEISS

86C-9-681-6

TASK 2 - SYSTEM ANALYSES
FLOW DIAGRAM

IN THE THROTTLING ENGINE ANALYSIS BRANCH OF THE TASK 2 FLOW DIAGRAM, THE DESIGN POINT ANALYSIS PROVIDES DATA TO THE OFF-DESIGN ANALYSIS WHICH, IN TURN, PROVIDES THE REQUIREMENTS FOR THE CONTROLS ANALYSIS. THE LATTER PROVIDES COMPONENT OPTIONS TO THE LIFE CYCLE ANALYSIS, WHERE THOSE OPTIONS ARE EVALUATED AND FINAL COMPONENT SELECTIONS ARE MADE. NOTE THAT THE CONTROL ANALYSIS HAS 2 BRANCHES; ONE IN WHICH THE CONTROLS ARE SELECTED FOR EACH INDIVIDUAL ENGINE, AND ONE IN WHICH THE GENERAL CONTROL SYSTEM COMPLEXITY (APPLICABLE TO ALL ENGINES) IS EXPLORED.

TASK 2 — SYSTEM ANALYSES FLOW DIAGRAM



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THROTTLING ENGINE COMPONENT SELECTION

THE PRELIMINARY COMPONENT SELECTIONS FOR THE THROTTLEABLE ENGINES ARE SHOWN. THESE WERE USED TO GENERATE THE THROTTLEABLE ENGINE DESIGN POINT BALANCES. THE ONLY ISSUE THAT IS SOMEWHAT IN QUESTION IS THE CHAMBER PRESSURE DESIGN CRITERION. THE RESOLUTION OF THIS ISSUE IS DISCUSSED ON THE NEXT FEW CHARTS.

THROTTLING ENGINE COMPONENT SELECTION FOR LOX/RP-1 AND LOX/CH4 ENGINES

COMPONENT/PARAMETER	TYPE/VALUE*	REASON
TURBOPUMP	750K	SUCTION PERFORMANCE
THRUST CONTROL	GG VALVES	RESPONSE
T/C MR CONTROL	MAIN VALVES	RESPONSE
MINIMUM VALVE $\Delta P/Pc$	0.1 AT 750K	CONTROLLABILITY
MINIMUM INJECTOR $\Delta P/Pc$	0.2 AT 625K	STABILITY
COOLING JACKET 100 MISSION LIFE	AT 625K	NOMINAL THRUST
NOZZLE DESIGN EXIT PRESSURE	6 psia AT 625K	NOMINAL VALUE
CHAMBER PRESSURE DESIGN CRITERION		
• FUEL-COOLED	MAXIMUM Isp_{VAC} AT 750K	HIGH PERFORMANCE AND LOW INERT WEIGHT
• LH_2-COOLED	3 STAGE LH_2 PUMP TIP SPEED LIMIT AT 750K	HIGH PERFORMANCE AND LOW INERT WEIGHT

*PERFORMANCE RELATED CRITERIA, ALL COMPONENT WEIGHTS REFLECT 750K STRESSES

86D-9-1889

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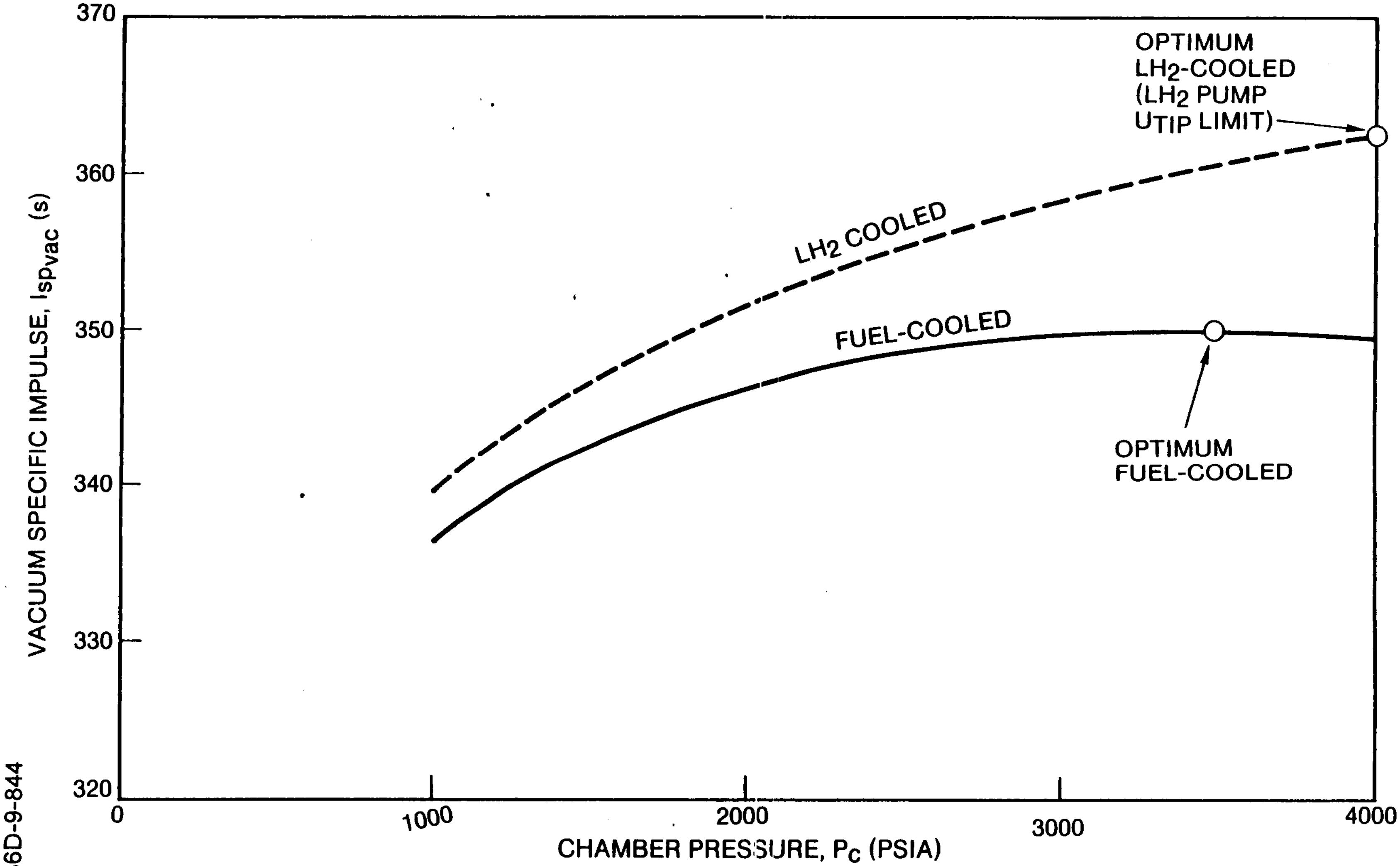
GG CYCLE PERFORMANCE OPTIMIZATION

FOR LH_2-COOLED GG CYCLE ENGINES, PERFORMANCE INCREASES STEADILY WITH CHAMBER PRESSURE UNTIL THE LH_2 PUMP TIP SPEED LIMIT IS REACHED. BECAUSE THAT TIP SPEED IS HIGHEST AT THE 750K OPERATING CONDITION, THAT POINT IS THE 750K OPERATING POINT, AND THE 625K OPERATING CONDITION IS OBTAINED BY THROTTLING THE ENGINE TO A LOWER CHAMBER PRESSURE.

FOR FUEL-COOLED GG CYCLE ENGINES, THE TREND IS NOT AS OBVIOUS BECAUSE THE PEAK PERFORMANCE OCCURS AT THE PEAK OF A VERY FLAT CURVE. AT THIS OPTIMUM CHAMBER PRESSURE, ENGINE WEIGHT IS INCREASING AND PROPELLANT BULK DENSITY IS DECREASING. BOTH OF THESE COULD SIGNIFICANTLY EFFECT THE ENGINE CHAMBER PRESSURE SELECTION BECAUSE THE PERFORMANCE CURVE IS SO FLAT. ALSO, FOR AN ENGINE WITH TWO OPERATING POINTS, THERE IS A QUESTION AS TO THE OPERATING POINT AT WHICH TO OPTIMIZE THE PERFORMANCE.

GG CYCLE PERFORMANCE OPTIMIZATION



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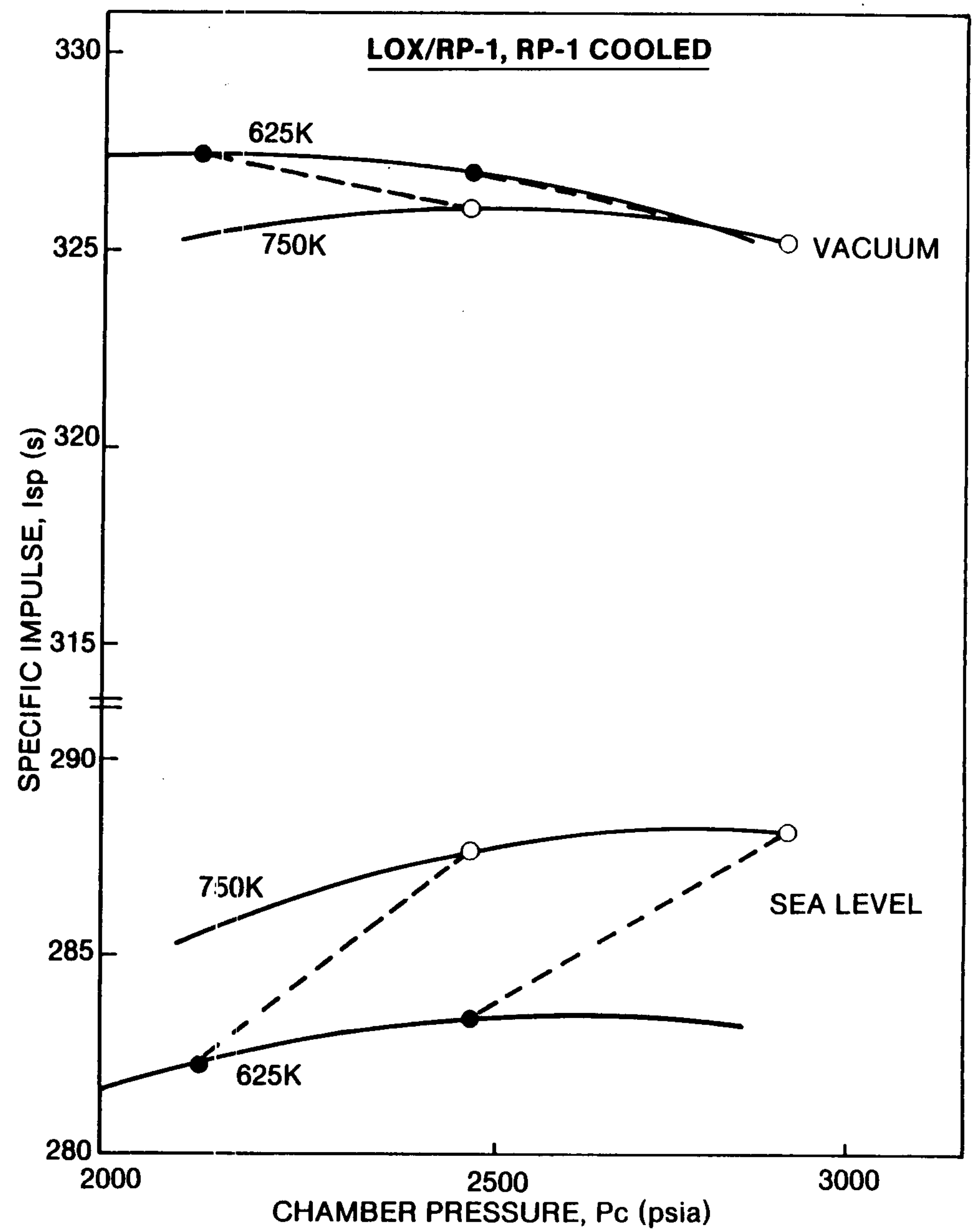
EFFECT OF FUEL-COOLED ENGINE CHAMBER PRESSURE ON SPECIFIC IMPULSE

TO DETERMINE THE APPROPRIATE APPROACH FOR SETTING THE CHAMBER PRESSURE FOR FUEL-COOLED ENGINES, 750K FUEL-COOLED LOX/RP-1 DESIGNS WERE ESTABLISHED AS A FUNCTION OF Pc, AND EACH WAS THROTTLED DOWN TO 625K. THE RESULTING PERFORMANCES ARE SHOWN HERE. EACH DASHED LINE CONNECTS A 750K OPERATING POINT TO THE 625K OPERATING POINT FOR THAT SAME ENGINE. THIS FIGURE SHOWS THAT THROTTLING IMPROVES VACUUM PERFORMANCE SLIGHTLY, AND SIGNIFICANTLY DECREASES SEA LEVEL PERFORMANCE.

EFFECT OF FUEL-COOLED ENGINE CHAMBER PRESSURE ON SPECIFIC IMPULSE



86D-9-1887

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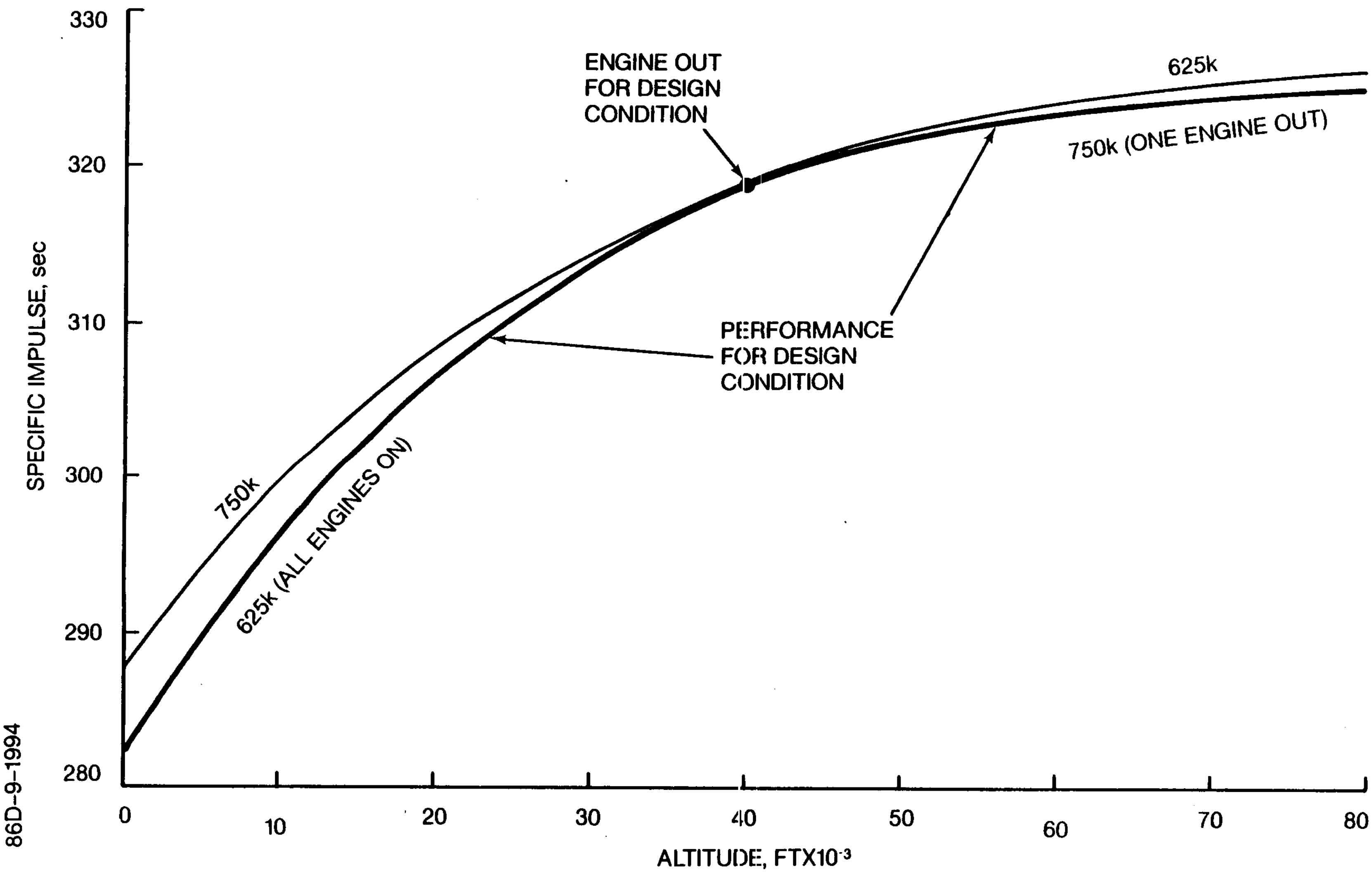
ENGINE PERFORMANCE FOR VEHICLE DESIGN CONDITION

THE VEHICLE DESIGN CONDITION OCCURS AT THE ENGINE OPERATING CONDITION THAT YIELDS THE WORST OVERALL PERFORMANCE. FOR A VEHICLE WITH AN ENGINE OUT CAPABILITY, THIS CONDITION OCCURS WHEN THE ENGINE GOES OUT AT THAT ALTITUDE AT WHICH THE PERFORMANCE FOR ALL ENGINES OPERATING EQUALS THAT FOR ONE ENGINE OUT. THIS RESULTS IN OPERATION AT THE LOWEST OF THE PERFORMANCE CURVES OVER THE ENTIRE FLIGHT TRAJECTORY.

ENGINE PERFORMANCE FOR VEHICLE DESIGN CONDITION



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ANALYTICAL RELATIONSHIPS

THESE ARE THE ANALYTICAL RELATIONSHIPS THAT WERE USED TO EVALUATE THE IMPACT OF FUEL-COOLED ENGINE CHAMBER PRESSURE ON THE VEHICLE. THE FIRST IS AN APPROXIMATION OF THE AVERAGE ENGINE SPECIFIC IMPULSE THAT OCCURS AS THE ENGINE PASSES FROM SEA LEVEL TO ALTITUDE AT THE PREVIOUSLY DESCRIBED VEHICLE DESIGN CONDITION. THE SECOND IS THE EXPRESSION FOR THE PROPELLANT BULK DENSITY FOR ENGINES THAT ARE NOT HYDROGEN COOLED. THE THIRD IS THE RELATIVE VEHICLE INERT WEIGHT EXPRESSION THAT TRANSLATES THE ENGINE PARAMETERS INTO VEHICLE INERT WEIGHT WHICH, IN TURN, IS AN INDICATOR OF RELATIVE VEHICLE COST.

ANALYTICAL RELATIONSHIPS

- VEHICLE $\Delta W_{INERT}{}^{*} = -638(Isp_{AVG} - Isp_{REF\ AVG}) + 1.61(6)(W - W_{REF}) - 848(\rho_B - \rho_{B\ REF})$
  - $Isp_{AVG} \approx Isp_{S/L_{MIN}} + 0.75(Isp_{VAC_{MIN}} - Isp_{S/L_{MIN}})$
  - $\rho_B = \dfrac{MR_E + 1}{\dfrac{MR_E}{\rho_O} + \dfrac{1}{\rho_F}}$

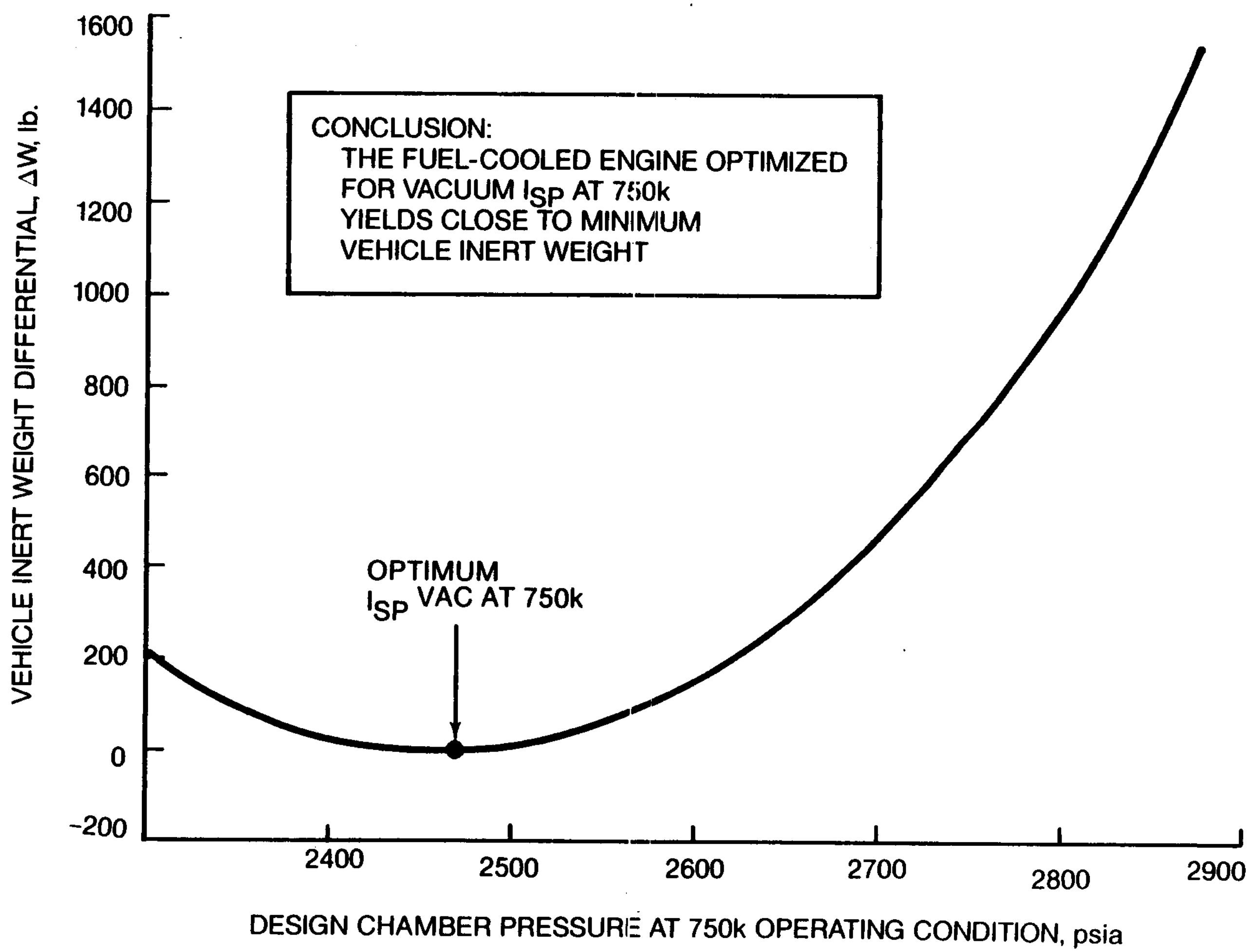
*VEHICLE EXCHANGE FACTOR FROM STAS CONTRACTORS

EFFECT OF DESIGN CHAMBER PRESSURE ON VEHICLE INERT WEIGHT FOR FUEL-COOLED, LOX/RP-1, GG CYCLE ENGINES

THIS CURVE SHOWS HOW THE VEHICLE INERT WEIGHT AT THE VEHICLE DESIGN CONDITION VARIES WITH DESIGN CHAMBER PRESSURE WHEN THE ENGINES ARE OPERATING AT 750K. IT ALSO SHOWS THAT THE ENGINE DESIGN CHAMBER PRESSURE AT WHICH OPTIMUM VACUUM SPECIFIC IMPULSE (Isp_{vac}) OCCURS ALSO YIELDS VERY CLOSE TO THE MINIMUM VEHICLE INERT WEIGHT. IT MAY THEN BE CONCLUDED THAT OPTIMIZING Isp_{vac} AT 750K IS A SATISFACTORY DESIGN CHAMBER PRESSURE SELECTION CRITERION FOR FUEL-COOLED GG CYCLE ENGINES.

EFFECT OF DESIGN CHAMBER PRESSURE ON VEHICLE INERT WEIGHT FOR ENGINE 1

LOX/RP-1, RP-1 COOLED



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FUEL-COOLED THROTTLING ENGINE BALANCE SUMMARY

THIS IS THE RESULTING THROTTLING ENGINE BALANCE SUMMARY, AT 750K SEA LEVEL THRUST, FOR ENGINES 1 AND 3, WHICH ARE RP-1-COOLED LOX/RP-1 AND CH_4-COOLED LOX/CH_4 GAS GENERATOR CYCLES, RESPECTIVELY. OF THE SIMPLE GG CYCLE ENGINES, THESE REPRESENT THE HIGHEST AND THE LOWEST FUEL (AND COOLANT) DENSITIES.

FUEL-COOLED THROTTLING ENGINE BALANCE SUMMARY

ENGINE PARAMETER DESCRIPTION	LOX/RP-1 (ENGINE 1)	LOX/CH_4 (ENGINE 3)
ENGINE SEA LEVEL THRUST (klb)	750.00	750.00
ENGINE VACUUM THRUST (klb)	850.10	838.76
ENGINE VACUUM ISP (s)	326.04	346.93
ENGINE SEA LEVEL ISP (s)	287.65	310.21
T/C VACUUM ISP (s)	339.25	358.10
GG VACUUM ISP (s)	137.65	160.71
MAIN CHAMBER PRESSURE (psia)	2468	3417
GG CHAMBER PRESSURE (psia)	2468	3417
ENGINE MIXTURE RATIO (O/F)	2.421	2.998
T/C MIXTURE RATIO (O/F)	2.800	3.500
GG MIXTURE RATIO (O/F)	0.412	0.398
ENGINE FUEL FLOW RATE (lb/s)	762.2	604.8
ENGINE OXIDIZER FLOW RATE (lb/s)	1845.2	1812.9
T/C FUEL FLOW RATE (lb/s)	641.2	506.9
T/C OXIDIZER FLOW RATE (lb/s)	1795.3	1774.0
GG GAS FLOW RATE (lb/s)	170.9	136.7
COMBUSTOR JACKET DISCHARGE TEMPERATURE (°R)	842	456
NOZZLE JACKET DISCHARGE TEMPERATURE (°R)	1102	607
GG TEMPERATURE (°R)	2000	2000

FUEL-COOLED THROTTLING ENGINE BALANCE SUMMARY (CONTINUED)

ENGINE PARAMETER DESCRIPTION	LOX/RP-1 (ENGINE 1)	LOX/CH_4 (ENGINE 3)
MAIN FUEL INJECTOR ΔP (psid/% Pc)	592/24	683/20
MAIN OXIDIZER INJECTOR ΔP (psid/% Pc)	592/24	820/24
GG FUEL INJECTOR ΔP (psid/% Pc)	592/24	683/20
GG OXIDIZER INJECTOR ΔP (psid/% Pc)	592/24	820/24
FUEL PUMP SPEED (rpm)	12,030	18,262
OXIDIZER PUMP SPEED (rpm)	12,030	13,140
HPFP DISCHARGE PRESSURE (psia)	3863	5220
HPOP DISCHARGE PRESSURE (psia)	3455	4784
FKP DISCHARGE PRESSURE (psia)	7530	6383
HPFP EFFICIENCY (%)	73.53	71.59
HPOP EFFICIENCY (%)	80.69	79.92
FKP EFFICIENCY (%)	65.29	80.76
HPFT EFFICIENCY (%)	62.82	72.19
HPOT EFFICIENCY (%)	N/A	76.94
HPFT HORSEPOWER (hp)	60,315	47,687
HPOT HORSEPOWER (hp)	N/A	39,218
ENGINE WEIGHT (lb)	7354	7713
MFV-1 ΔP/Pc (%)	10.0	10.0
MFV-2 ΔP/Pc (%)	10.0	10.0
MOV ΔP/Pc (%)	10.0	10.0
GGFV ΔP/Pc (%)	29.5	10.0
GGOV ΔP/Pc (%)	10.0	10.0

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LH_2-COOLED THROTTLING ENGINE BALANCE SUMMARY

THESE ARE THE CORRESPONDING BALANCES FOR THE CORRESPONDING HYDROGEN COOLED ENGINES, WHICH ARE ENGINES 4 AND 6 (LOX/RP-1 AND LOX/CH_4, RESPECTIVELY). OF THE HYDROGEN-COOLED GG CYCLE ENGINES, THESE HAVE THE HIGHEST AND THE LOWEST THRUST CHAMBER FUEL DENSITIES.

THE COMPONENT SELECTION AND SELECTION PROCEDURES ARE SIMILAR TO THOSE FOR THE PREVIOUS FUEL-COOLED ENGINES. AS DISCUSSED EARLIER, THE PROCEDURE FOR OPTIMIZING THE 750K ENGINE FOR VACUUM PERFORMANCE IS DIFFERENT. FOR HYDROGEN-COOLED ENGINES, THE MAXIMUM PERFORMANCE OCCURS AT THE HYDROGEN PUMP TIP SPEED LIMIT WHICH, IN TURN, OCCURS AT THE MAXIMUM THRUST OPERATING POINT, WHICH IS 750K.

LH_2-COOLED THROTTLING ENGINE BALANCE SUMMARY

ENGINE PARAMETER DESCRIPTION	$LOX/RP\text{-}1/LH_2$ (ENGINE 4)	$LOX/CH_4/LH_2$ (ENGINE 6)
ENGINE SEA LEVEL THRUST (klb)	750.00	750.00
ENGINE VACUUM THRUST (klb)	833.70	832.91
ENGINE VACUUM ISP (s)	345.85	358.73
ENGINE SEA LEVEL ISP (s)	311.13	323.03
T/C VACUUM ISP (s)	345.52	359.02
GG VACUUM ISP (s)	364.69	347.00
MAIN CHAMBER PRESSURE (psia)	4025	4075
GG CHAMBER PRESSURE (psia)	4025	4075
T/C MIXTURE RATIO (O/F)	2.800	3.500
GG MIXTURE RATIO (O/F)	0.340	0.474
T/C AND ENGINE FUEL FLOW RATE (lb/s)	623.3	503.5
ENGINE OXIDIZER FLOW RATE (lb/s)	1755.8	1780.3
T/C OXIDIZER FLOW RATE (lb/s)	1745.2	1762.3
LH_2 FLOW RATE (lb/s)	31.4	38.0
GG GAS FLOW RATE (lb/s)	41.9	56.0
COMBUSTOR JACKET DISCHARGE TEMPERATURE (°R)	532.9	453.2
NOZZLE JACKET DISCHARGE TEMPERATURE (°R)	1369.9	1142.5
GG TEMPERATURE (°R)	2000.0	2000.0

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LH_2-COOLED THROTTLING ENGINE BALANCE SUMMARY (CONTINUED)

ENGINE PARAMETER DESCRIPTION	LOX/RP-1/LH_2 (ENGINE 4)	LOX/CH_4/LH_2 (ENGINE 6)
MAIN FUEL INJECTOR ΔP (psid/% Pc)	966/24	978/24
MAIN OXIDIZER INJECTOR ΔP (psid/% Pc)	966/24	978/24
GG FUEL INJECTOR ΔP (psid/% Pc)	805/20	815/20
GG OXIDIZER INJECTOR ΔP (psid/% Pc)	966/24	978/24
MAIN TURBOPUMP SPEED (rpm)	13,300	13,370
LH_2 TURBOPUMP SPEED (rpm)	60,000	60,000
FUEL PUMP DISCHARGE PRESSURE (psia)	5635	5705
LOX PUMP DISCHARGE PRESSURE (psia)	5635	5705
LH_2 PUMP DISCHARGE PRESSURE (psia)	6578	6672
FUEL PUMP EFFICIENCY (%)	77.6	72.7
LOX PUMP EFFICIENCY (%)	78.7	78.8
LH_2 PUMP EFFICIENCY (%)	70.1	72.4
MAIN TURBINE EFFICIENCY (%)	50.1	52.3
LH_2 TURBINE EFFICIENCY (%)	50.1	52.3
MAIN TURBINE HORSEPOWER (hp)	69,050	85,600
LH_2 TURBINE HORSEPOWER (hp)	16,710	19,570
ENGINE WEIGHT (lb)	7334	7515
MFV ΔP/Pc (%)	10.0	10.0
MH2V ΔP/Pc (%)	2.5	2.5
MOV ΔP/Pc (%)	10.0	10.0
GGH2V ΔP/Pc (%)	10.0	10.0
GGOV ΔP/Pc (%)	10.0	10.0

PRELIMINARY STEADY-STATE OFF-DESIGN STUDY FOR LOX/RP-1 AND LOX/CH_4 FUEL-COOLED GAS GENERATOR CYCLES

THIS SECTION PRESENTS THE PRELIMINARY STEADY-STATE OFF-DESIGN STUDY CONDUCTED FOR THE FUEL-COOLED LOX/RP-1 (ENGINE 1) AND LOX/CH_4 (ENGINE 3) ENGINES.

PRELIMINARY STEADY-STATE OFF-DESIGN STUDY

- ENGINE 1 — LOX/RP-1, RP-1 COOLED
- ENGINE 3 — LOX/CH_4, CH_4 COOLED

OBJECTIVE AND ANALYTICAL APPROACH

THESE ARE THE OBJECTIVE, CRITERIA AND ANALYTICAL APPROACH WHICH WERE USED IN THE PRELIMINARY STEADY-STATE OFF-DESIGN STUDY FOR THE FUEL-COOLED LOX/RP-1 AND LOX/CH_4 ENGINES.

OBJECTIVE AND ANALYTICAL APPROACH

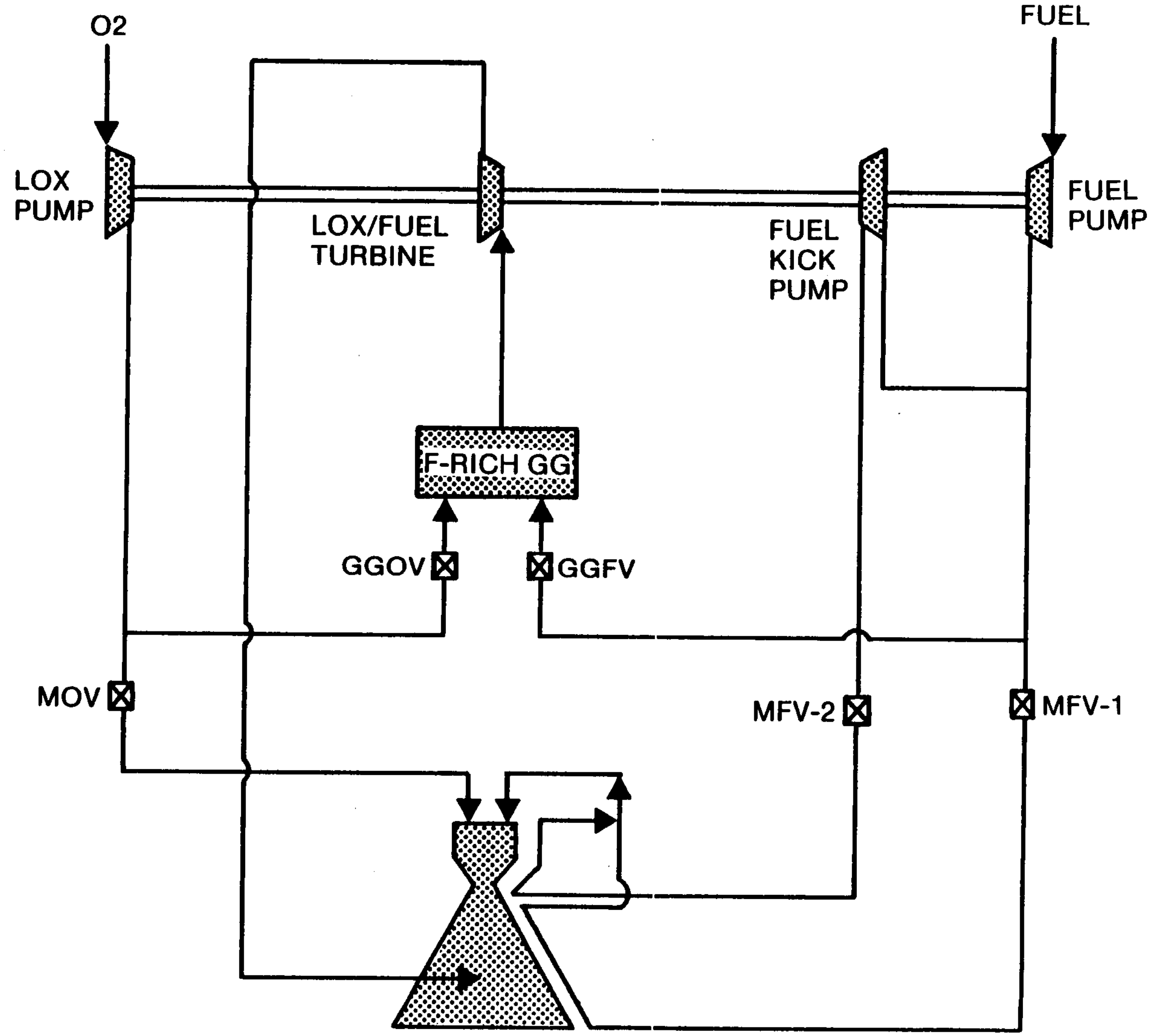
- **OBJECTIVE**
  - SELECT THRUST AND MIXTURE RATIO CONTROL VALVES BASED ON:
    - MINIMUM VEHICLE INERT WEIGHT
    - MINIMUM PROPELLANT CONSUMPTION
    - MAXIMUM VALVE ΔP MARGINS
    - ENGINE SENSITIVITIES
    - START/CUTOFF REQUIREMENTS
- **ANALYTICAL APPROACH**
  - UPGRADE EXISTING BOOSTER ENGINE OFF-DESIGN CODE TO MODEL DETAILED STEADY-STATE OPERATION OF THE LOX/HC ENGINES
  - CONDUCT SENSITIVITY STUDY ON CONTROL VALVES
  - PERFORM ENGINE THROTTLING PERFORMANCE ANALYSIS WITH DIFFERENT THRUST AND MIXTURE RATIO CONTROL OPTIONS

86D-9-1853

ENGINE 1 FLOW SCHEMATIC

THIS IS THE FLOW CIRCUIT OF THE FUEL-COOLED LOX/RP-1 (ENGINE 1) ENGINE BEING STUDIED.

ENGINE 1 FLOW SCHEMATIC
LOX/RP-1, RP-1 COOLED



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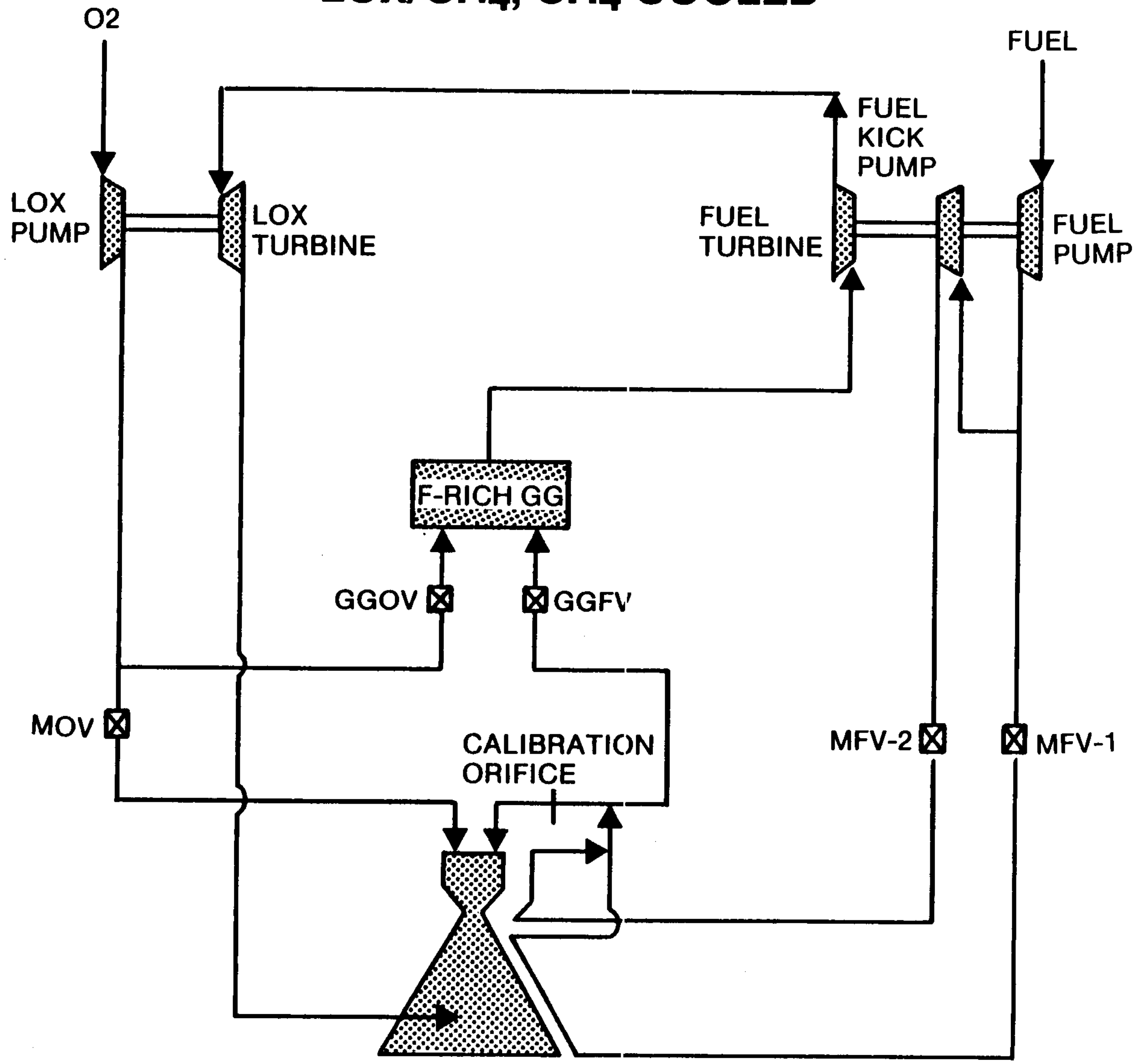
ENGINE 3 FLOW SCHEMATIC

THIS IS THE FLOW CIRCUIT OF THE FUEL-COOLED LOX/CH_4 (ENGINE 3) ENGINES BEING STUDIED. IT ALSO REPRESENTS THE LOX/C_3H_8 (ENGINE 2) ENGINE.

ENGINE 3 FLOW SCHEMATIC
LOX/CH_4, CH_4 COOLED



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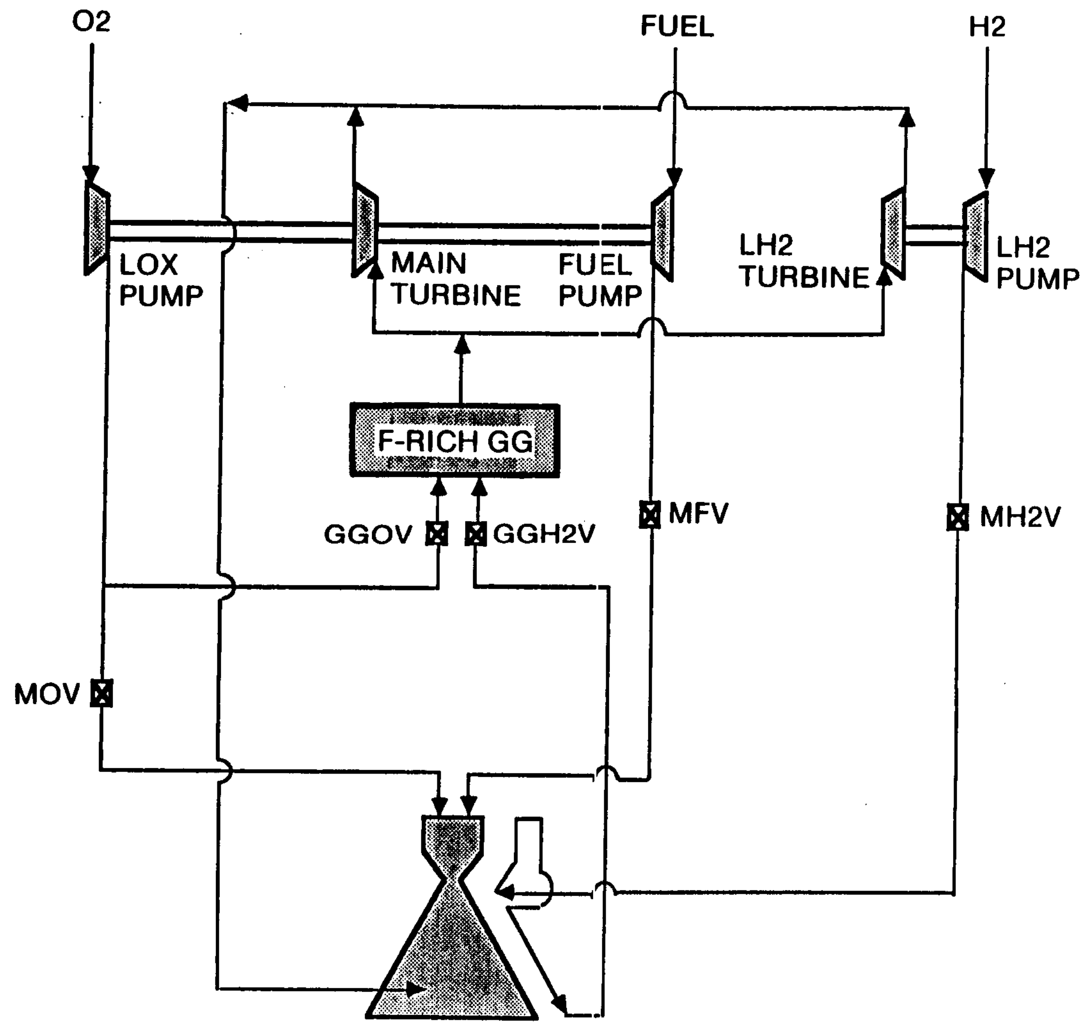
LH_2-COOLED ENGINE FLOW SCHEMATIC

THIS IS THE FLOW CIRCUIT OF THE LH_2-COOLED LOX/RP-1 (ENGINE 4), LOX/CH_4 (ENGINE 6) AND LOX/C_3H_8 (ENGINE 5) ENGINES BEING STUDIED.

LH2-COOLED ENGINE FLOW SCHEMATIC
ENGINES 4, 5, AND 6



86D-9-1972

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OVERALL GROUNDRULES/ASSUMPTIONS

THESE ARE THE GENERAL GROUNDRULES AND ASSUMPTIONS USED IN THE PRELIMINARY STEADY-STATE OFF-DESIGN STUDY FOR THE FUEL-COOLED LOX/RP-1 AND LOX/CH_4 ENGINES.

OVERALL GROUNDRULES/ASSUMPTIONS

- **MUST COMPLETE THE MISSION WITH EITHER SIX OR FIVE ENGINES**
- **ENGINE PARAMETERS TO BE CONTROLLED:**
  - ENGINE THRUST
  - ENGINE OR T/C MIXTURE RATIO
  - COOLANT FLOW SPLIT
  - GG MIXTURE RATIO (OPTIONAL)
- **KEEP GG TEMPERATURE LESS THAN OR EQUAL TO 2000°R***
- **MAINTAIN COOLANT FLOW SPLIT AT 50/50 OF ENGINE FLOW RATE***
- **MINIMUM THRUST/MR CONTROL VALVE ΔP = 10% OF OPERATING P_c**
- **CONSTANT BOOSTER ENGINE BURN TIME OF 160 s**

*ON-DESIGN OPERATING CONDITION

SENSITIVITY STUDY
GROUNDRULES/ASSUMPTIONS

THESE ARE THE GROUNDRULES AND ASSUMPTIONS USED ONLY IN THE SENSITIVITY STUDY FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

SENSITIVITY STUDY

- **GROUNDRULES/ASSUMPTIONS**
  - VARY ONE VALVE AT A TIME AND REBALANCE THE ENGINE
  - NO CONSTRAINT ON GG TEMPERATURE
  - ONLY CONDUCT SENSITIVITY STUDY FOR ENGINE 1 — LOX/RP-1, RP-1 COOLED
  - EXPECT SIMILAR SENSITIVITIES FOR ENGINE 2 — LOX/C_3H_8, C_3H_8 COOLED AND ENGINE 3 — LOX/CH_4, CH_4 COOLED

INFLUENCE COEFFICIENTS

THESE ARE THE INFLUENCE COEFFICIENTS WITH CONTROL VALVES CALCULATED FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

INFLUENCE COEFFICIENTS*

DEPENDENT VARIABLES	INDEPENDENT VARIABLES				
	MFV-1	MFV-2	MOV	GGFV	GGOV
SEA LEVEL THRUST	0.045	0.039	0.080	-0.443	0.290
T/C MIXTURE RATIO	-0.118	-0.107	0.104	0.008	-0.022
ENGINE MIXTURE RATIO	-0.100	-0.107	0.095	-0.076	0.012
AVERAGE ISP	-0.003	-0.011	0.009	-0.040	0.021
MAIN CHAMBER PRESSURE	0.073	0.065	0.146	-0.394	0.244
GG CHAMBER PRESSURE	0.023	0.053	0.106	-0.415	0.376
GG TEMPERATURE	-0.005	-0.072	-0.003	-0.389	0.198

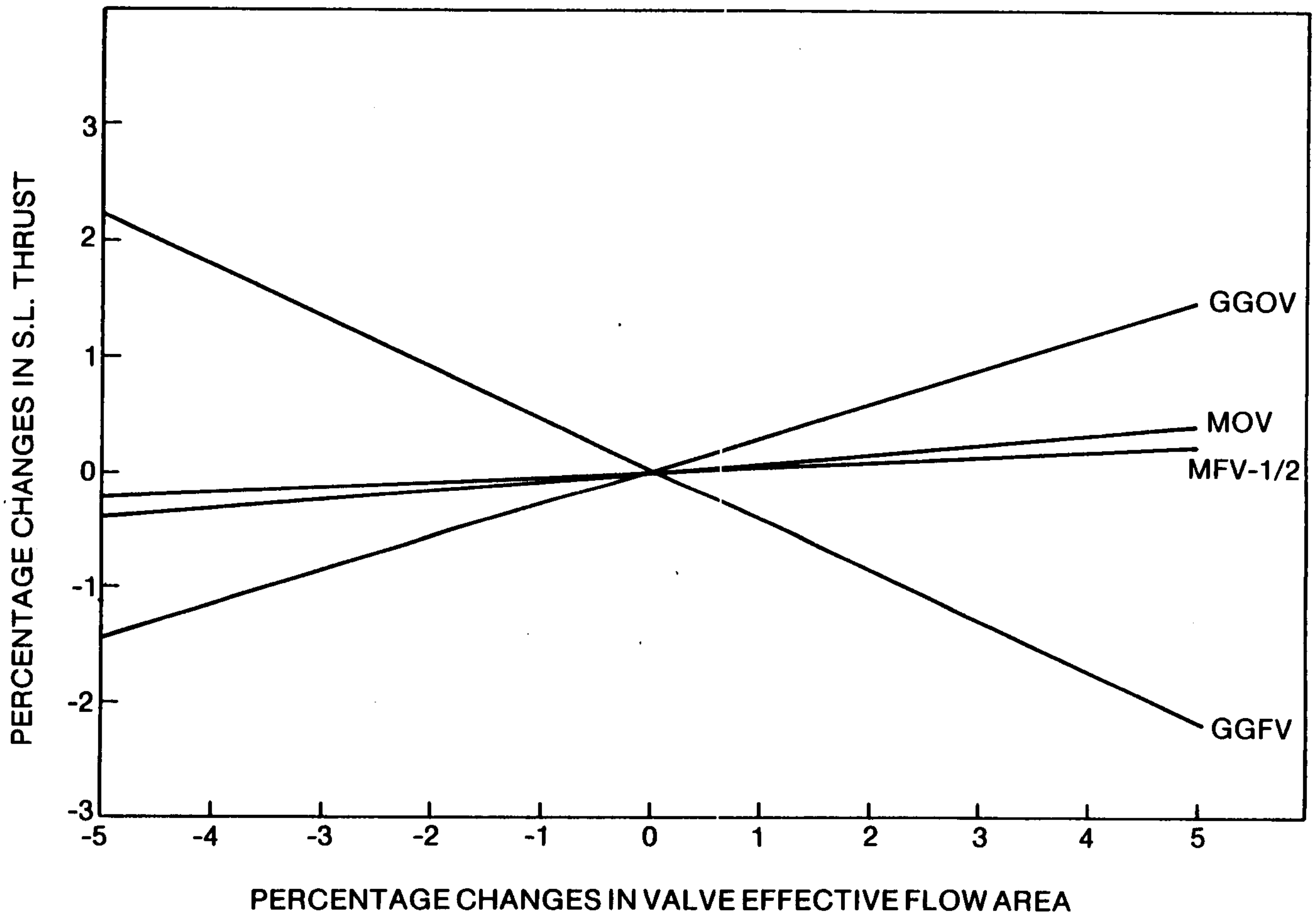
*INFLUENCE COEFFICIENT = PERCENTAGE CHANGE IN DEPENDENT VARIABLE PER ONE PERCENTAGE CHANGE IN THE INDEPENDENT VARIABLE

86D-9-1858

ENGINE THRUST SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON ENGINE SEA LEVEL THRUST FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

ENGINE THRUST SENSITIVITIES



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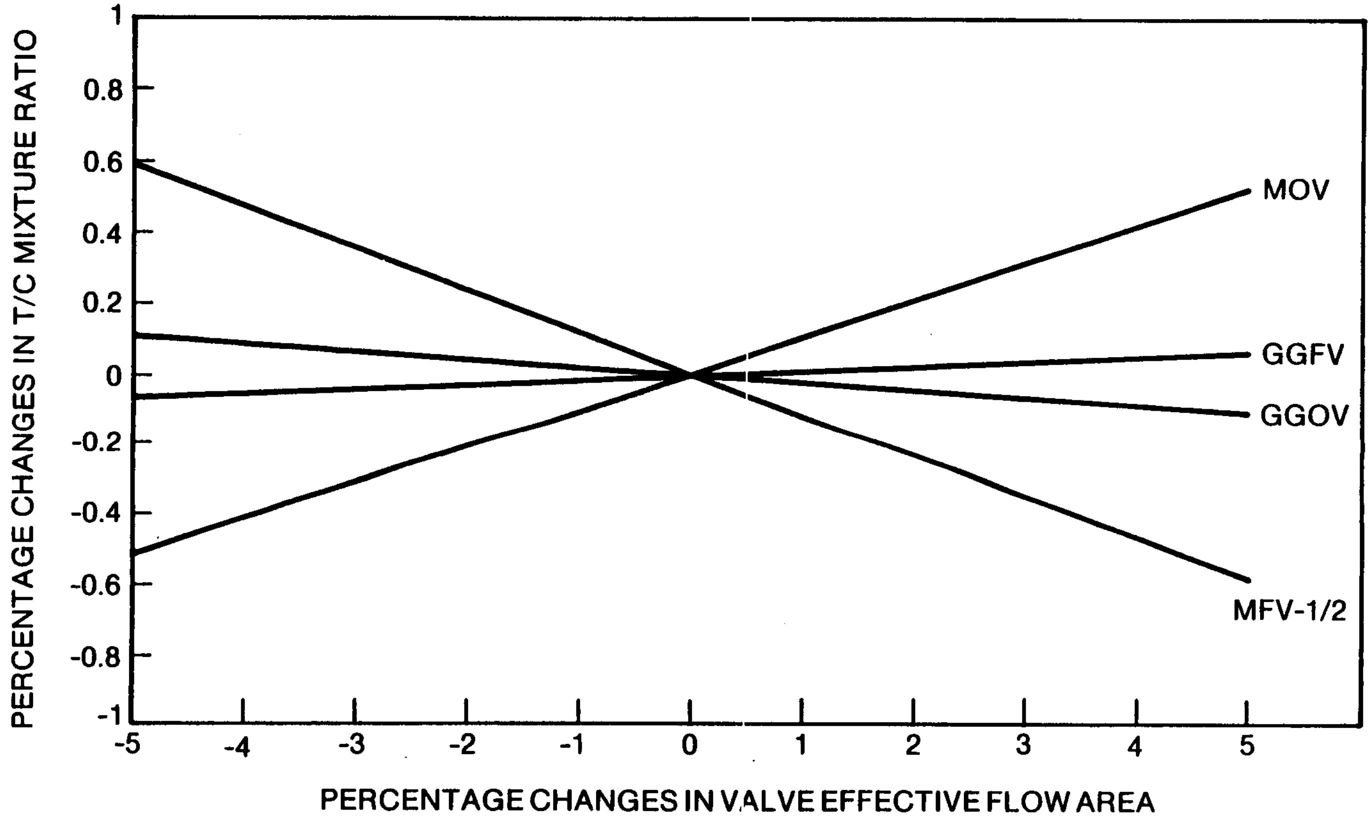
T/C MIXTURE RATIO SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON T/C MIXTURE RATIO FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

T/C MIXTURE RATIO SENSITIVITIES



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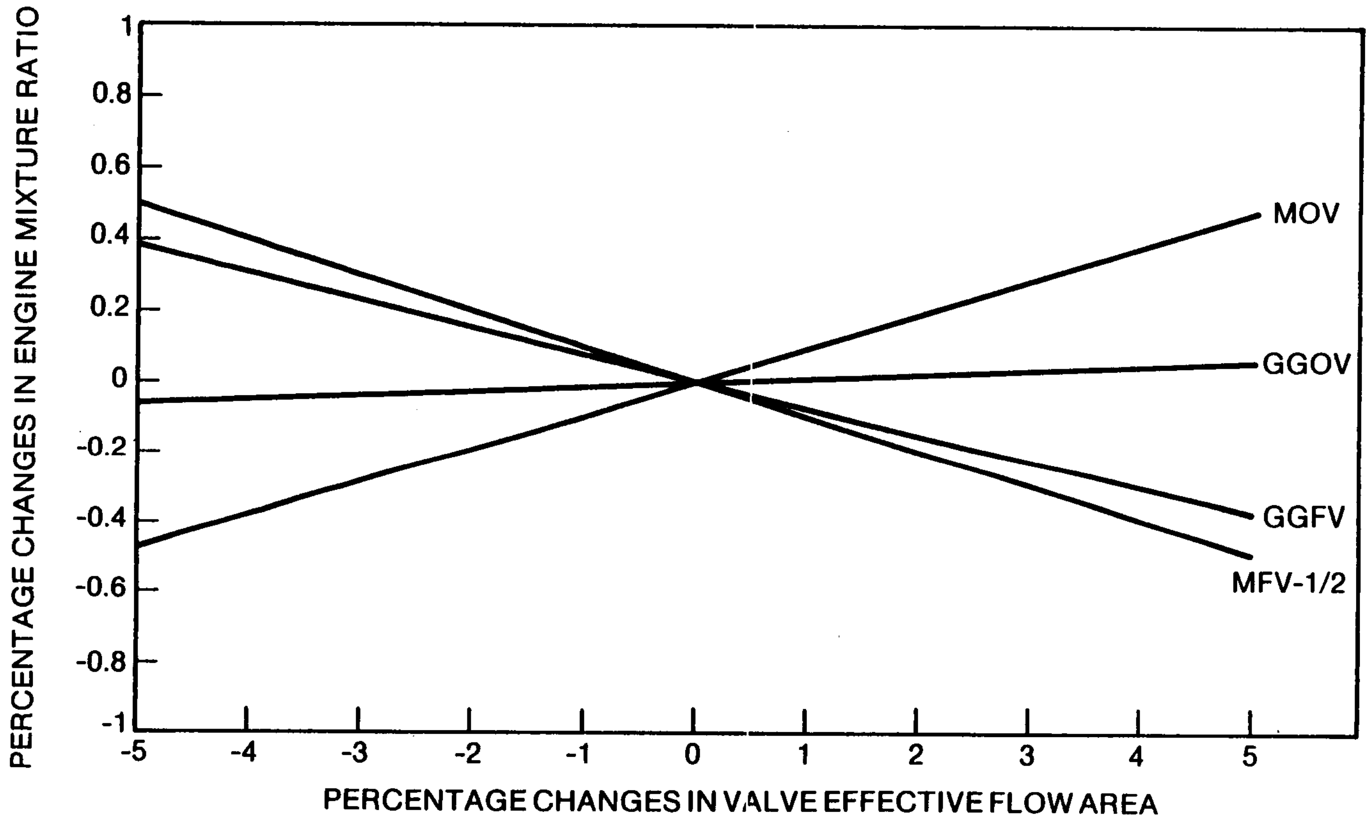
ENGINE MIXTURE RATIO SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON ENGINE MIXTURE RATIO FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

ENGINE MIXTURE RATIO SENSITIVITIES



86D-9-1861

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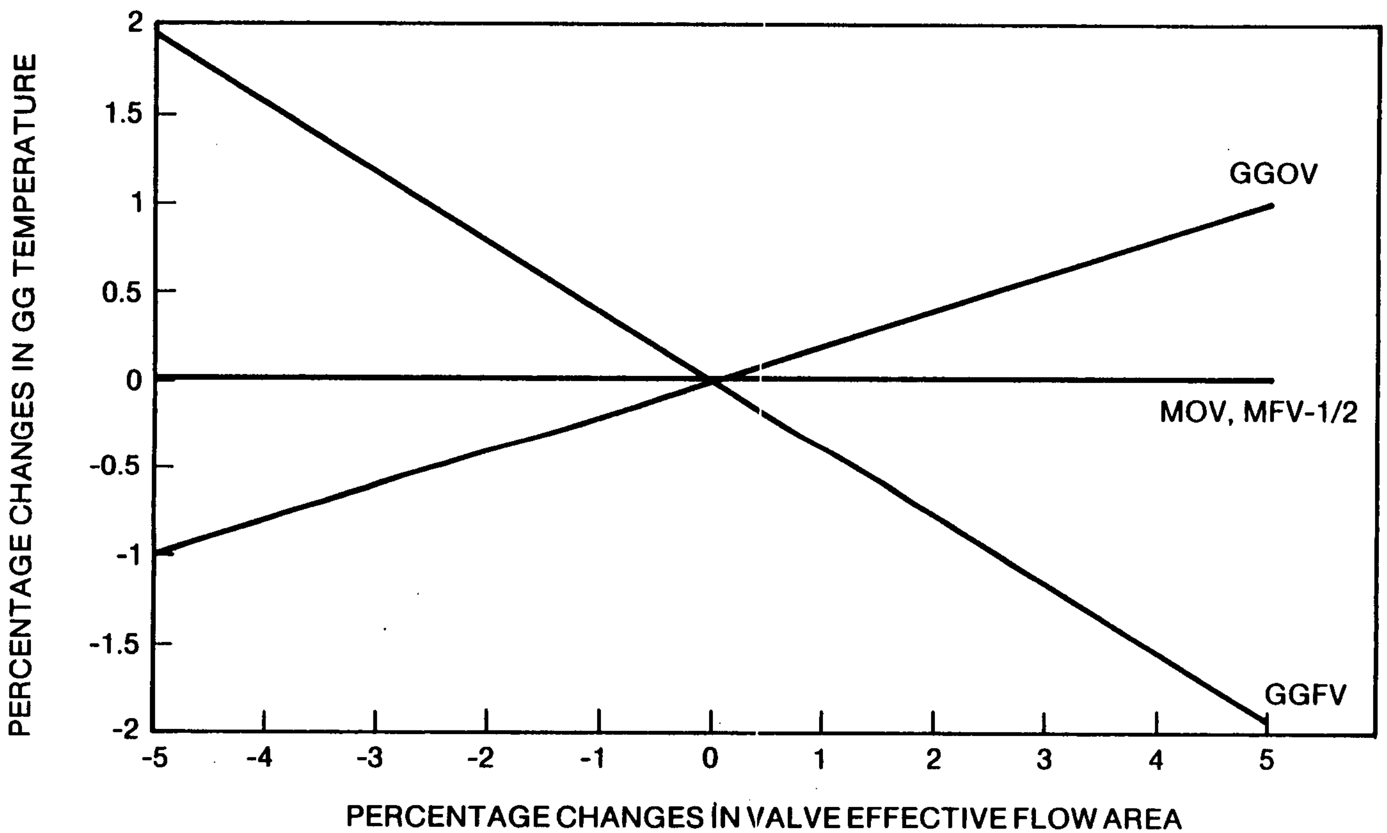
GG TEMPERATURE SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON GG TEMPERATURE FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

GG TEMPERATURE SENSITIVITIES



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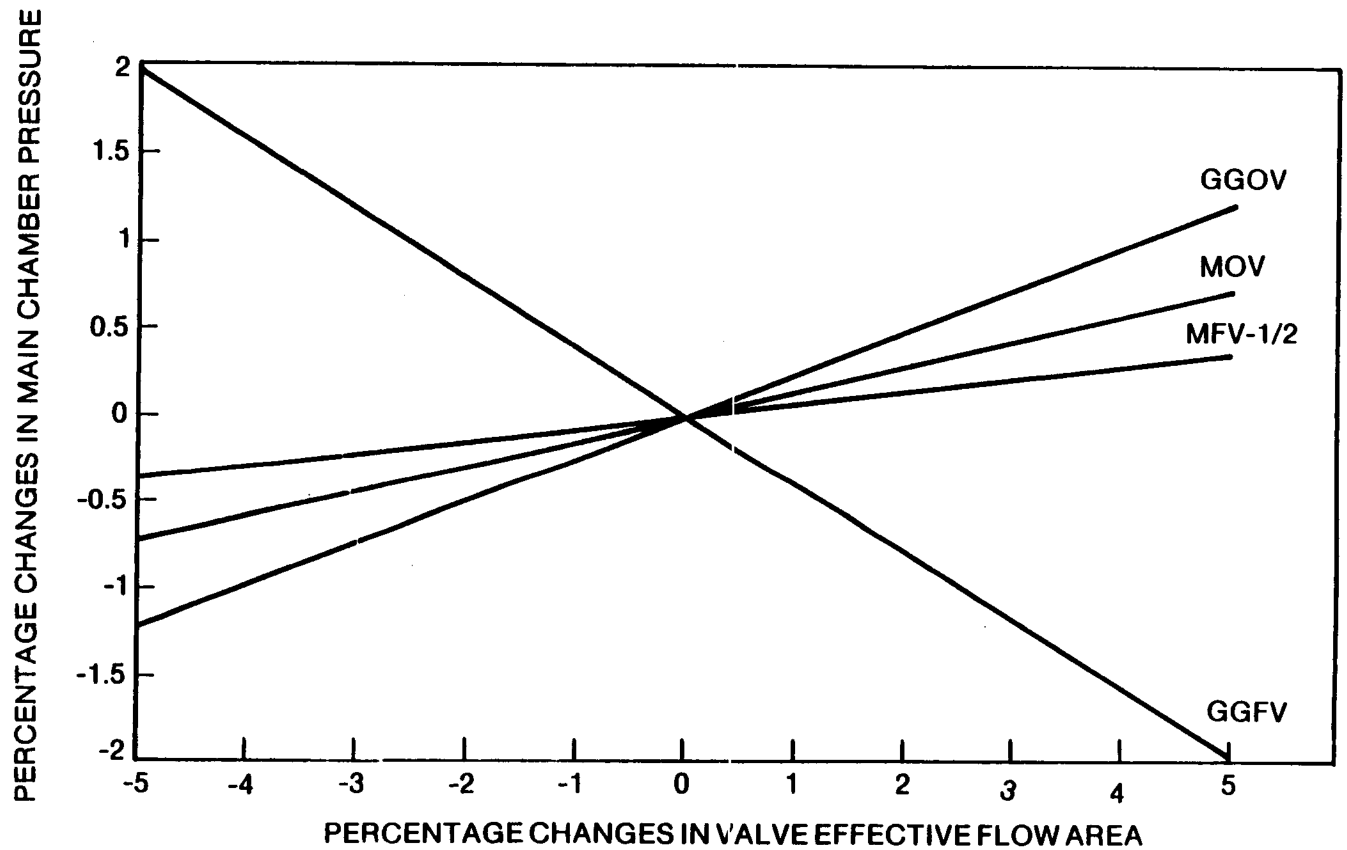
MAIN CHAMBER PRESSURE SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON MAIN CHAMBER PRESSURE FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

MAIN CHAMBER PRESSURE SENSITIVITIES



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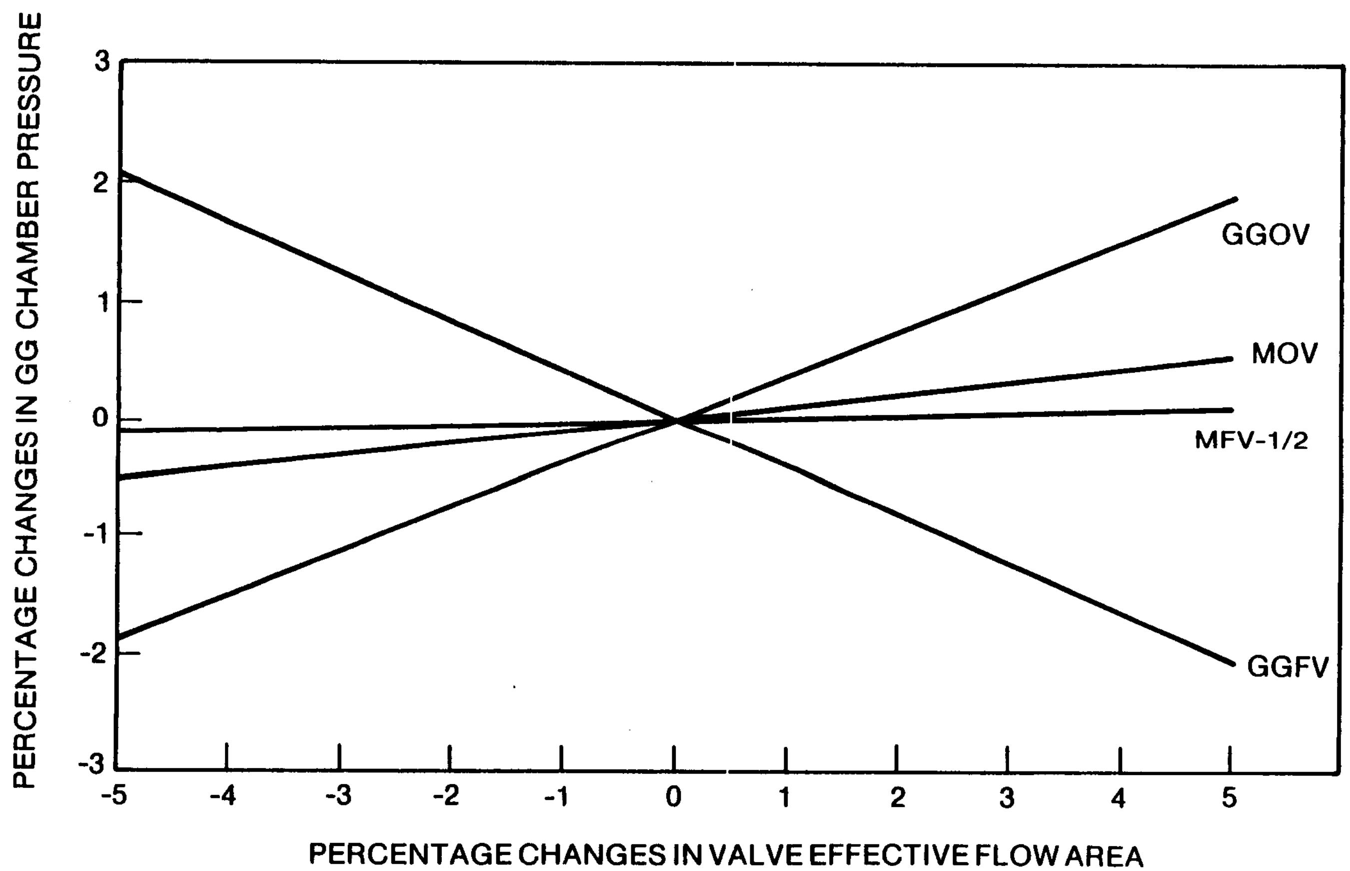
GG CHAMBER PRESSURE SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON GG CHAMBER PRESSURE FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

GG CHAMBER PRESSURE SENSITIVITIES



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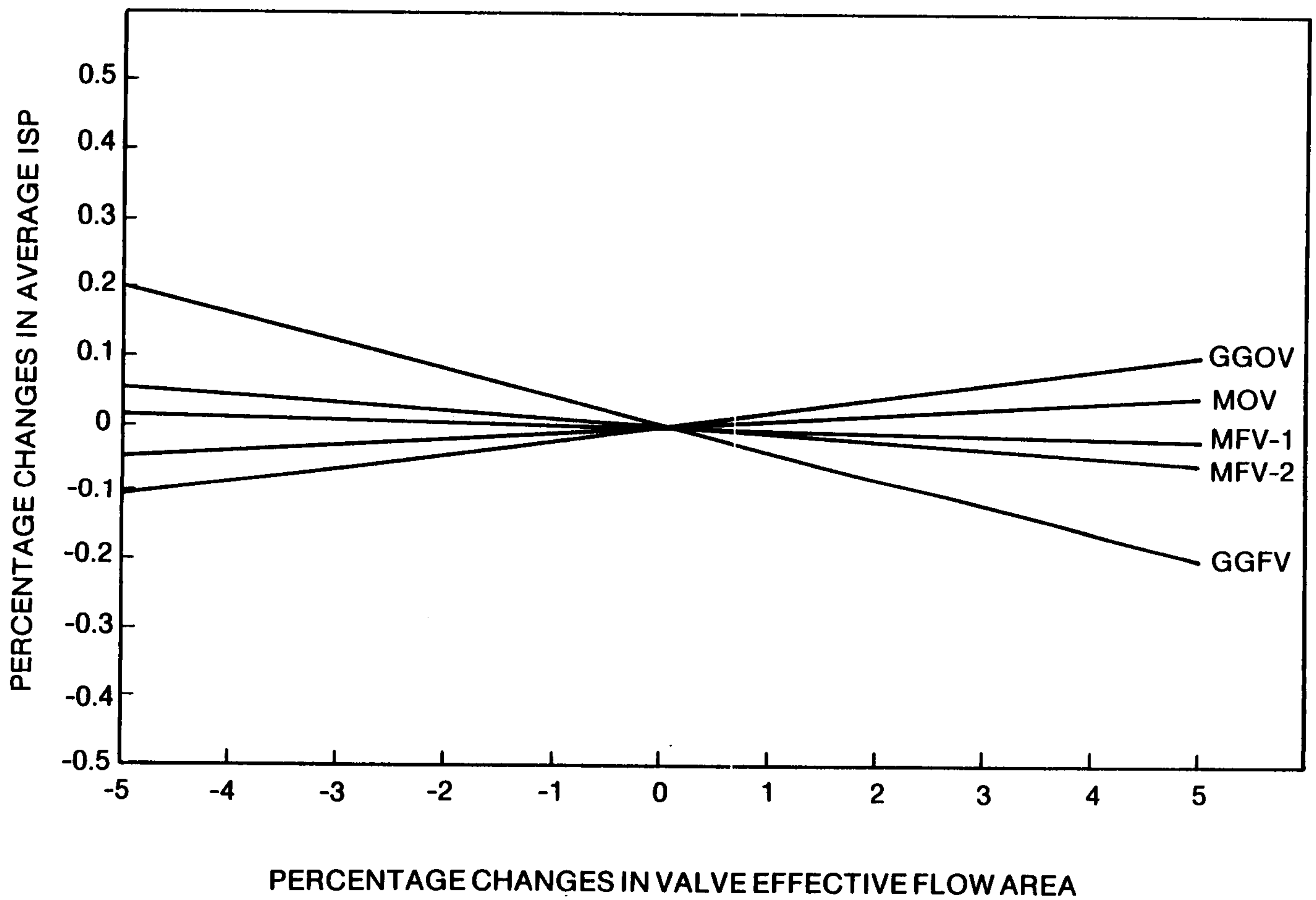
PERFORMANCE SENSITIVITIES

THESE ARE THE EFFECTS OF THROTTLING VALVES ON AVERAGE SPECIFIC IMPULSE FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

PERFORMANCE SENSITIVITIES



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SENSITIVITY STUDY
RESULTS/CONCLUSIONS

THESE ARE THE RESULTS AND CONCLUSIONS FROM THE PRELIMINARY SENSITIVITY STUDY CONDUCTED FOR THE FUEL-COOLED LOX/RP-1 ENGINE.

SENSITIVITY STUDY

- **RESULTS/CONCLUSIONS**
  - T/C AND ENGINE MIXTURE RATIOS ARE MUCH MORE SENSITIVE TO MFV-1, MFV-2, AND MOV THAN OTHER VALVES
  - ENGINE THRUST IS MUCH MORE SENSITIVE TO GGOV AND GGFV THAN OTHER VALVES
  - GG TEMPERATURE IS MUCH MORE SENSITIVE TO GGOV AND GGFV THAN OTHER VALVES
  - USE MOV, MFV-1, OR MFV-2 FOR T/C OR ENGINE MIXTURE RATIO CONTROL
  - USE GGOV AND/OR GGFV FOR THRUST AND/OR GG MIXTURE RATIO CONTROL
  - USE MFV-1 OR MFV-2 FOR COOLANT FLOW SPLIT CONTROL

ENGINE THROTTLING PERFORMANCE ANALYSIS
GROUNDRULES/ASSUMPTIONS

THESE ARE THE GROUNDRULES AND ASSUMPTIONS USED IN THE ENGINE THROTTLING PERFORMANCE ANALYSIS FOR THE FUEL-COOLED LOX/RP-1 AND LOX/CH_4 ENGINES.

ENGINE THROTTLING PERFORMANCE ANALYSIS

- **GROUNDRULES/ASSUMPTIONS**
  - MUST COMPLETE THE MISSION WITH EITHER SIX OR FIVE ENGINES
  - FIXED THROTTLED THRUST = 625 klb AT SEA LEVEL
  - KEEP GG TEMPERATURE LESS THAN OR EQUAL TO 2000°R*
  - MAINTAIN COOLANT FLOW SPLIT AT 50/50 OF ENGINE FLOW RATE*
  - MINIMUM THRUST/MR CONTROL VALVE ΔP = 10% OF OPERATING Pc
  - CONSTANT BOOSTER ENGINE BURN TIME OF 160 s
  - USE LOX/RP-1 ENGINE 1 AND LOX/CH4 ENGINE 3 WITH 625K NOZZLE AS "ON-DESIGN"

*ON-DESIGN OPERATING CONDITION

86D-9-1867

THRUST AND MIXTURE RATIO CONTROL OPTIONS FOR THROTTLING

THESE ARE THE VARIOUS THRUST AND MIXTURE RATIO CONTROL OPTIONS BEING INVESTIGATED FOR THE FUEL-COOLED LOX/RP-1 AND LOX/CH_4 ENGINES AT THROTTLING CONDITION.

THRUST AND MIXTURE RATIO CONTROL OPTIONS FOR THROTTLING

T/C OR ENGINE MR CONTROL	ENGINE THRUST CONTROL	
	GGOV/GGFV USED*	**GGOV USED****
MFVs USED	OPTION I: 1. GGOV = THRUST CONTROL 2. MFV-2 = MR CONTROL 3. MFV-1 = COOLANT CONTROL 4. GGFV = GG MR CONTROL NO. OF CONTROL VALVES = 4	OPTION III: 1. GGOV = THRUST CONTROL 2. MFV-2 = MR CONTROL 3. MFV-1 = COOLANT CONTROL NO. OF CONTROL VALVES = 3
MOV USED	OPTION II: 1. GGOV = THRUST CONTROL 2. MOV = MR CONTROL 3. MFV-2 = COOLANT CONTROL 4. GGFV = GG MR CONTROL NO. OF CONTROL VALVES = 4	OPTION IV: 1. GGOV = THRUST CONTROL 2. MOV= MR CONTROL 3. MFV-2 = COOLANT CONTROL NO. OF CONTROL VALVES = 3

*GG MIXTURE RATIO IS CONTROLLED
**GG MIXTURE RATIO IS NOT CONTROLLED

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LOX/RP-1 ENGINE 1 BALANCE SUMMARY
WITH T/C MIXTURE RATIO CONTROL

THIS TABLE SUMMARIZES THE ENGINE PERFORMANCE AND OPERATING CHARACTERISTICS AT NOMINAL AND OFF-NOMINAL CONDITIONS FOR THE FUEL-COOLED LOX/RP-1 ENGINE WITH T/C MIXTURE RATIO CONTROL; I.E., CONSTANT T/C MIXTURE RATIO.

LOX/RP-1 ENGINE 1 BALANCE SUMMARY WITH T/C MIXTURE RATIO CONTROL

ENGINE PARAMETER DESCRIPTION	ON DESIGN	THRUST AND MR CONTROL OPTION			
		I	II	III	IV
ENGINE SEA LEVEL THRUST (klb)	750.00	625.00	625.00	625.00	625.00
ENGINE VACUUM THRUST (klb)	850.10	725.12	725.14	725.12	725.12
AVERAGE ISP (s)	316.44	316.10	315.92	312.81	312.71
ENGINE VACUUM ISP (s)	326.04	327.40	327.21	323.99	323.89
ENGINE SEA LEVEL ISP (s)	287.65	282.20	282.03	279.26	279.17
MAIN CHAMBER PRESSURE (psia)	2468	2118	2117	2111	2110
GG CHAMBER PRESSURE (psia)	2468	1742	1774	1952	1976
ENGINE MIXTURE RATIO (O/F)	2.421	2.477	2.472	2.386	2.383
T/C MIXTURE RATIO (O/F)	2.800	2.800	2.800	2.800	2.800
GG MIXTURE RATIO (O/F)	0.412	0.412	0.412	0.355	0.356
GG TEMPERATURE (°R)	2000	1991	1992	1791	1796
ENGINE FUEL FLOW RATE (lb/s)	762.2	636.9	638.2	661.1	661.8
ENGINE OXIDIZER FLOW RATE (lb/s)	1845.2	1577.8	1577.9	1577.0	1577.0
NUMBER OF THROTTLING VALVES USED (NONE)	TBD	4	4	3	3
MFV-1 ΔP/Pc (%)	10.0	6.5	N/A	6.1	N/A
MFV-2 ΔP/Pc (%)	10.0	28.5	33.1	14.9	18.7
MOV ΔP/Pc (%)	10.0	N/A	11.4	N/A	11.3
GGFV ΔP/Pc (%)	29.5	52.4	53.1	N/A	N/A
GGOV ΔP/Pc (%)	10.0	33.0	33.7	19.0	20.1

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LOX/RP-1 ENGINE 1 BALANCE SUMMARY
WITH ENGINE MIXTURE RATIO CONTROL

THIS TABLE SUMMARIZES THE ENGINE PERFORMANCE AND OPERATING CHARACTERISTICS AT NOMINAL AND OFF-NOMINAL CONDITIONS FOR THE FUEL-COOLED LOX/RP-1 ENGINE WITH ENGINE MIXTURE RATIO CONTROL; I.E., CONSTANT ENGINE MIXTURE RATIO.

LOX/RP-1 ENGINE 1 BALANCE SUMMARY WITH ENGINE MIXTURE RATIO CONTROL

ENGINE PARAMETER DESCRIPTION	ON DESIGN	THRUST AND MR CONTROL OPTION			
		I	II	III	IV
ENGINE SEA LEVEL THRUST (klb)	750.00	625.00	625.00	625.00	625.00
ENGINE VACUUM THRUST (klb)	850.10	725.12	725.12	725.12	725.13
AVERAGE ISP (s)	316.44	315.96	315.58	312.87	312.86
ENGINE VACUUM ISP (s)	326.04	327.25	326.86	324.06	324.04
ENGINE SEA LEVEL ISP (s)	287.65	282.07	281.73	279.31	279.30
MAIN CHAMBER PRESSURE (psia)	2468	2126	2123	2106	2105
GG CHAMBER PRESSURE (psia)	2468	1741	1806	1949	1959
ENGINE MIXTURE RATIO (O/F)	2.421	2.421	2.421	2.421	2.421
T/C MIXTURE RATIO (O/F)	2.800	2.728	2.742	2.849	2.850
GG MIXTURE RATIO (O/F)	0.412	0.412	0.412	0.353	0.354
GG TEMPERATURE (°R)	2000	1994	1991	1786	1790
ENGINE FUEL FLOW RATE (lb/s)	762.2	647.6	648.5	654.3	654.2
ENGINE OXIDIZER FLOW RATE (lb/s)	1845.2	1568.2	1569.9	1583.4	1583.6
NUMBER OF THROTTLING VALVES USED (NONE)	TBD	4	4	3	3
MFV-1 $\Delta P/Pc$ (%)	10.0	3.0	N/A	7.3	N/A
MFV-2 $\Delta P/Pc$ (%)	10.0	20.7	30.9	25.7	20.9
MOV $\Delta P/Pc$ (%)	10.0	N/A	13.9	N/A	9.2
GGFV $\Delta P/Pc$ (%)	29.5	50.7	52.2	N/A	N/A
GGOV $\Delta P/Pc$ (%)	10.0	33.0	24.1	19.3	19.1

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LOX/CH_4 ENGINE 3 BALANCE SUMMARY WITH T/C MIXTURE RATIO CONTROL

THIS TABLE SUMMARIZES THE ENGINE PERFORMANCE AND OPERATING CHARACTERISTICS AT NOMINAL AND OFF-NOMINAL CONDITIONS FOR THE FUEL-COOLED LOX/CH_4 ENGINE WITH T/C MIXTURE RATIO CONTROL; I.E., CONSTANT T/C MIXTURE RATIO.

c-4

LOX/CH4 ENGINE 3 BALANCE SUMMARY WITH T/C MIXTURE RATIO CONTROL

ENGINE PARAMETER DESCRIPTION	ON DESIGN	THRUST AND MR CONTROL OPTION			
		I	II	III	IV
ENGINE SEA LEVEL THRUST (klb)	750.00	625.00	625.00	625.00	625.00
ENGINE VACUUM THRUST (klb)	838.76	713.79	713.79	713.80	713.79
AVERAGE ISP (s)	337.75	337.40	337.00	334.45	334.98
ENGINE VACUUM ISP (s)	346.93	348.23	347.82	345.18	345.73
ENGINE SEA LEVEL ISP (s)	310.21	304.91	304.55	302.24	302.72
MAIN CHAMBER PRESSURE (psia)	3417	2921	2918	2917	2914
GG CHAMBER PRESSURE (psia)	3417	2439	2550	2616	2715
ENGINE MIXTURE RATIO (O/F)	2.998	3.070	3.053	2.908	2.937
T/C MIXTURE RATIO (O/F)	3.500	3.500	3.500	3.500	3.500
GG MIXTURE RATIO (O/F)	0.398	0.398	0.398	0.233	0.279
GG TEMPERATURE (°R)	2000	2002	2003	1648	1775
ENGINE FUEL FLOW RATE (lb/s)	604.8	503.6	506.3	529.2	524.5
ENGINE OXIDIZER FLOW RATE (lb/s)	1812.9	1546.2	1545.9	1538.7	1540.2
NUMBER OF THROTTLING VALVES USED (NONE)	TBD	4	4	3	3
MFV-1 ΔP/Pc (%)	10.0	1.7	N/A	0.2	N/A
MFV-2 ΔP/Pc (%)	10.0	3.4	11.0	0.0	9.9
MOV ΔP/Pc (%)	10.0	N/A	15.2	N/A	17.7
GGFV ΔP/Pc (%)	10.0	34.2	28.8	N/A	N/A
GGOV ΔP/Pc (%)	10.0	31.5	32.8	30.2	33.0

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LOX/CH_4 ENGINE 3 BALANCE SUMMARY
WITH ENGINE MIXTURE MIXTURE RATIO CONTROL

THIS TABLE SUMMARIZES THE ENGINE PERFORMANCE AND OPERATING CHARACTERISTICS AT NOMINAL AND OFF-NOMINAL CONDITIONS FOR THE FUEL-COOLED LOX/CH_4 ENGINE WITH ENGINE MIXTURE RATIO CONTROL; I.E., CONSTANT ENGINE MIXTURE RATIO.

LOX/CH4 ENGINE 3 BALANCE SUMMARY WITH ENGINE MIXTURE RATIO CONTROL

ENGINE PARAMETER DESCRIPTION	ON DESIGN	THRUST AND MR CONTROL OPTION			
		I	II	III	IV
ENGINE SEA LEVEL THRUST (klb)	750.00	625.00	625.00	625.00	625.00
ENGINE VACUUM THRUST (klb)	838.76	715.78	715.77	715.77	717.76
AVERAGE ISP (s)	337.75	337.32	336.76	333.99	334.32
ENGINE VACUUM ISP (s)	346.93	348.36	347.78	344.92	345.27
ENGINE SEA LEVEL ISP (s)	310.21	304.19	303.68	301.18	301.48
MAIN CHAMBER PRESSURE (psia)	3417	2940	2932	2916	2915
GG CHAMBER PRESSURE (psia)	3417	2454	2607	2628	2680
ENGINE MIXTURE RATIO (O/F)	2.998	2.998	2.998	2.998	2.998
T/C MIXTURE RATIO (O/F)	3.500	3.408	3.439	3.603	3.586
GG MIXTURE RATIO (O/F)	0.398	0.398	0.398	0.247	0.269
GG TEMPERATURE (°R)	2000	2003	2001	1691	1752
ENGINE FUEL FLOW RATE (lb/s)	604.8	514.0	514.8	519.2	518.5
ENGINE OXIDIZER FLOW RATE (lb/s)	1812.9	1540.7	1543.3	1556.0	1554.5
NUMBER OF THROTTLING VALVES USED (NONE)	TBD	4	4	3	3
MFV-1 $\Delta P/Pc$ (%)	10.0	0.5	N/A	3.9	N/A
MFV-2 $\Delta P/Pc$ (%)	10.0	0.0	10.8	4.3	10
MOV $\Delta P/Pc$ (%)	10.0	N/A	18.3	N/A	13.7
GGFV $\Delta P/Pc$ (%)	10.0	34.9	27.0	N/A	N/A
GGOV $\Delta P/Pc$ (%)	10.0	30.9	33.6	29.7	31.3

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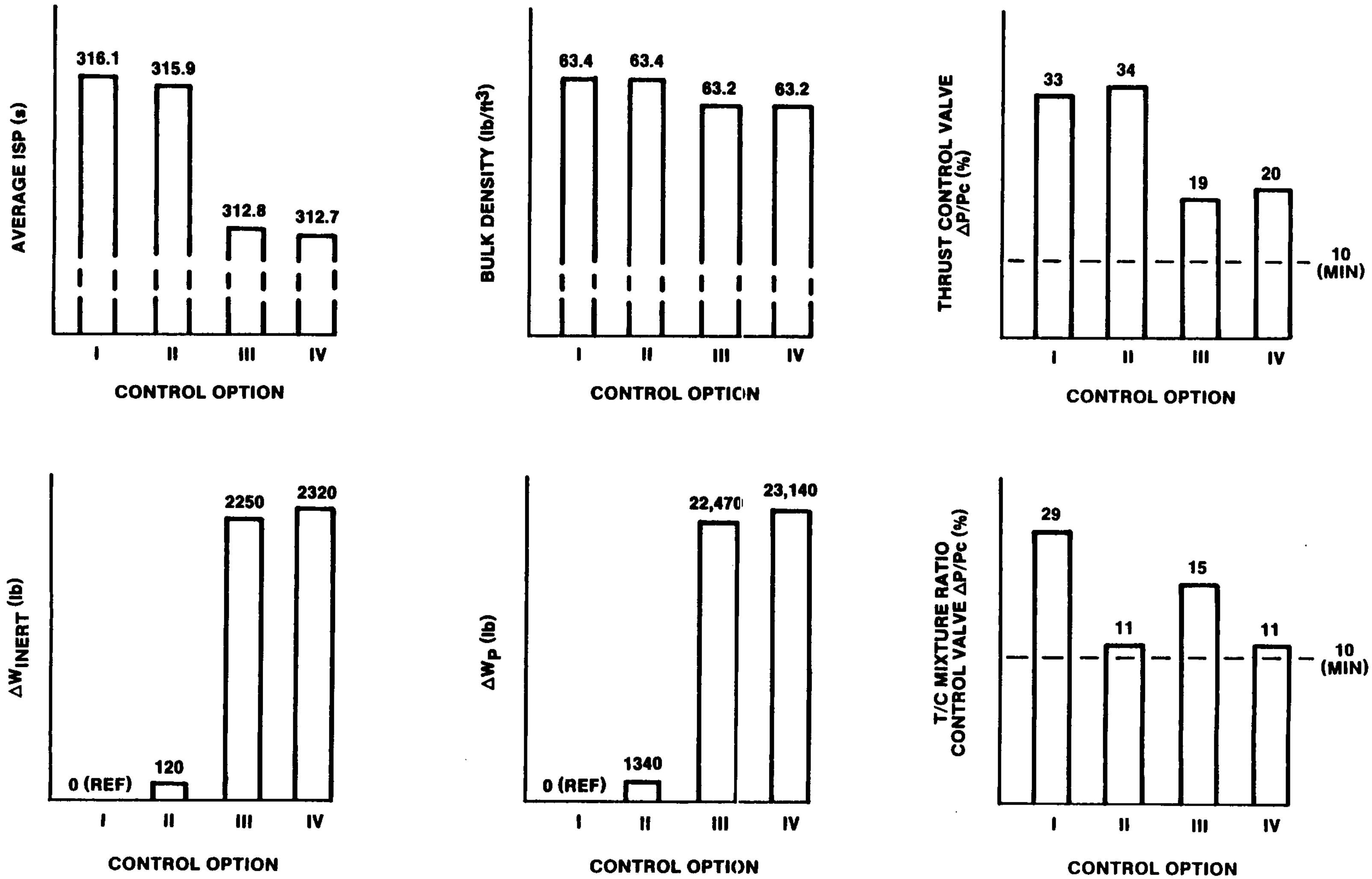
EFFECT OF CONTROL OPTIONS ON ENGINE 1, LOX/RP-1, RP-1 COOLED WITH T/C MIXTURE RATIO CONTROL

THIS CHART ILLUSTRATES THE EFFECT OF DIFFERENT THRUST AND MIXTURE RATIO CONTROL OPTIONS ON THE FUEL-COOLED LOX/RP-1 ENGINE AT THROTTLING CONDITION WITH CONSTANT T/C MIXTURE RATIO. IT SHOWS (CLOCK-WISE FROM TOP LEFT) THE AVERAGE SPECIFIC IMPULSE, PROPELLANT BULK DENSITY, THRUST CONTROL VALVE $\Delta P/Pc$ RATIO, T/C MIXTURE RATIO CONTROL VALVE $\Delta P/Pc$, TOTAL PROPELLANT CONSUMPTION AND VEHICLE INERT WEIGHT DIFFERENTIALS VS. THRUST AND T/C MIXTURE RATIO CONTROL OPTIONS.

CONTROL OPTION I WHICH RESULTS IN MINIMUM VEHICLE INERT WEIGHT DIFFERENTIAL WITH ADEQUATE VALVE ΔP MARGINS IS SELECTED FOR THE FUEL-COOLED LOX/RP-1 ENGINE. IN ADDITION, GG MIXTURE RATIO CONTROL IS RECOMMENDED FOR HIGH ENGINE PERFORMANCE.

EFFECT OF CONTROL OPTIONS ON ENGINE 1
LOX/RP-1, RP-1 COOLED
T/C MIXTURE RATIO CONTROL



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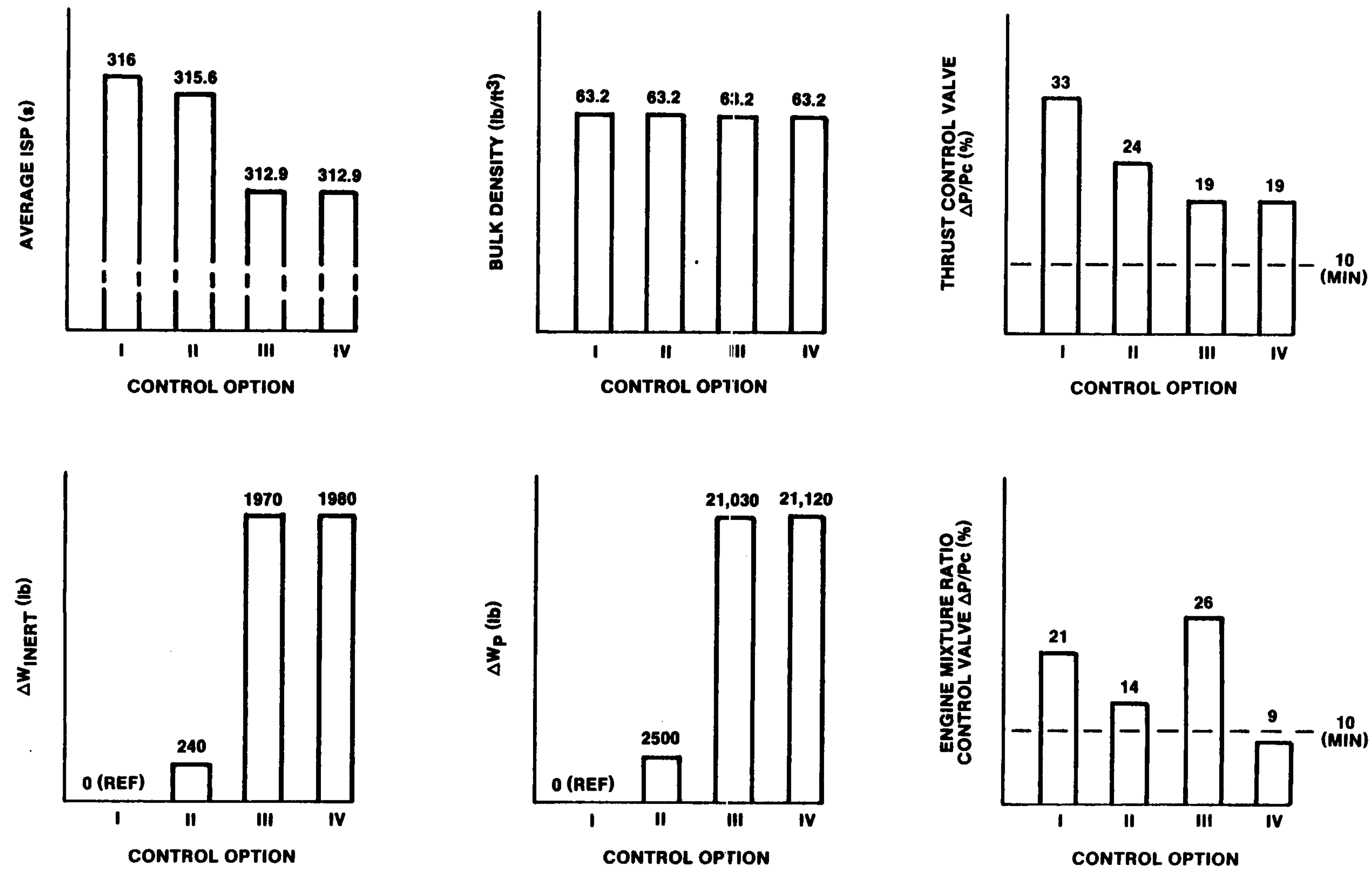
EFFECT OF CONTROL OPTIONS ON ENGINE 1
RP-1 COOLED WITH ENGINE MIXTURE RATIO CONTROL

THIS CHART ILLUSTRATES THE EFFECT OF DIFFERENT THRUST AND MIXTURE RATIO CONTROL OPTIONS ON THE FUEL-COOLED LOX/RP-1 ENGINE AT THROTTLING CONDITION WITH CONSTANT ENGINE MIXTURE RATIO. IT SHOWS (CLOCK-WISE FROM TOP LEFT) THE AVERAGE SPECIFIC IMPULSE, PROPELLANT BULK DENSITY, THRUST CONTROL VALVE $\Delta P/P_c$ RATIO, ENGINE MIXTURE RATIO CONTROL VALVE $\Delta P/P_c$, TOTAL PROPELLANT CONSUMPTION AND VEHICLE INERT WEIGHT DIFFERENTIALS VS. THRUST AND ENGINE MIXTURE RATIO CONTROL OPTIONS.

CONTROL OPTION I WHICH RESULTS IN MINIMUM VEHICLE INERT WEIGHT DIFFERENTIAL WITH ADEQUATE VALVE ΔP MARGINS IS SELECTED FOR THE FUEL-COOLED LOX/RP-1 ENGINE. IN ADDITION, GG MIXTURE RATIO CONTROL IS RECOMMENDED FOR HIGH ENGINE PERFORMANCE.

EFFECT OF CONTROL OPTIONS ON ENGINE 1
LOX/RP-1, RP-1 COOLED
ENGINE MIXTURE RATIO CONTROL



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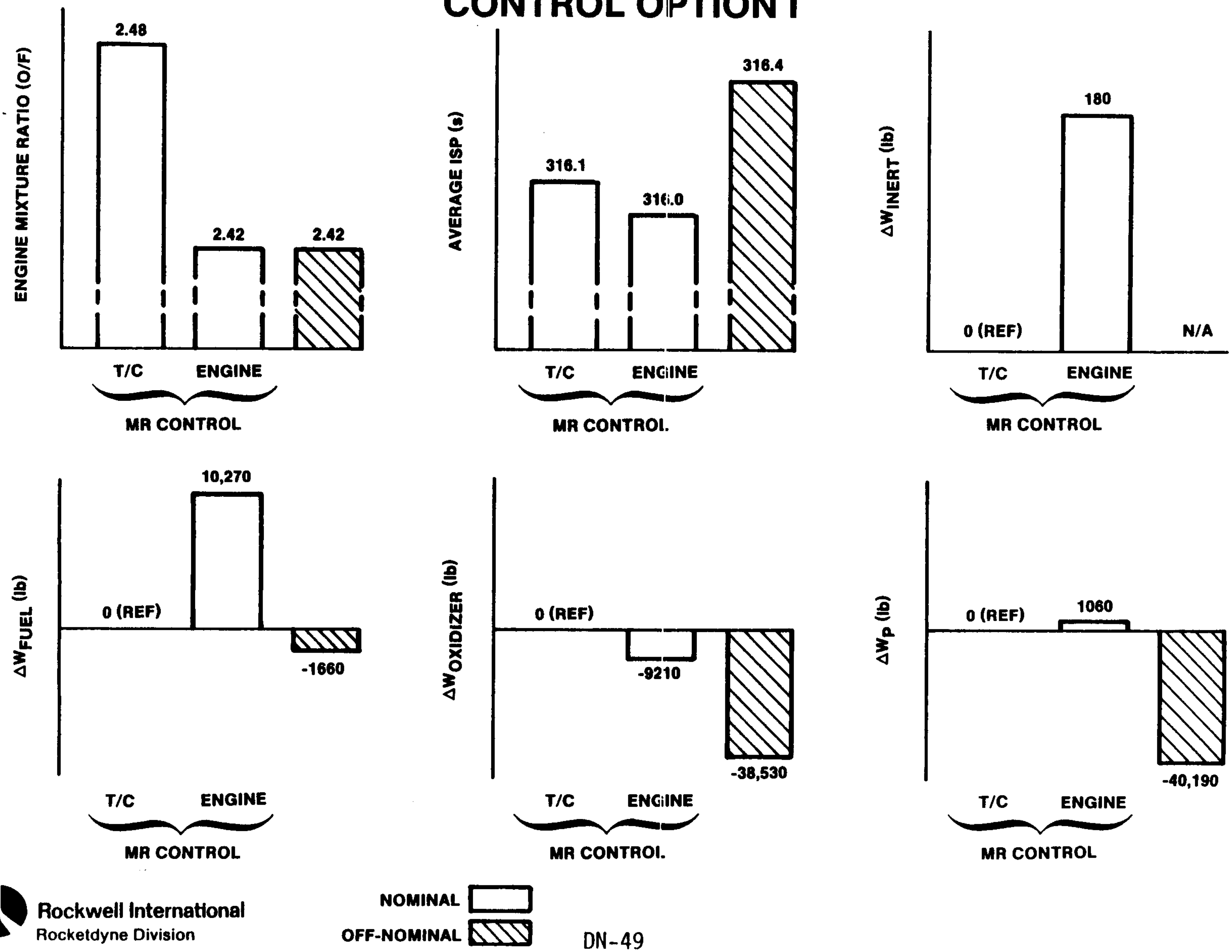
EFFECT OF T/C AND ENGINE MIXTURE RATIO CONTROL ON ENGINE 1 AT NOMINAL/OFF-NOMINAL CONDITIONS WITH SELECTED CONTROL OPTION I

THIS CHART ILLUSTRATES THE EFFECT OF T/C AND MIXTURE RATIO CONTROLS ON THE FUEL-COOLED LOX/RP-1 ENGINE AT NOMINAL AND OFF-NOMINAL OPERATING CONDITIONS. IT SHOWS (CLOCK-WISE FROM TOP LEFT) ENGINE MIXTURE RATIO, AVERAGE SPECIFIC IMPULSE, VEHICLE INERT WEIGHT DIFFERENTIAL, TOTAL PROPELLANT, LOX AND RP-1 CONSUMPTION DIFFERENTIALS VS. ENGINE OPERATING CONDITIONS AND MIXTURE RATIO CONTROLS. THE CONTROL OPTION I SELECTED PREVIOUSLY IS USED FOR THROTTLING; I.E., NOMINAL OPERATING CONDITION.

EFFECT OF T/C AND ENGINE MR CONTROL ON ENGINE 1 AT NOMINAL/OFF-NOMINAL CONDITIONS

CONTROL OPTION I



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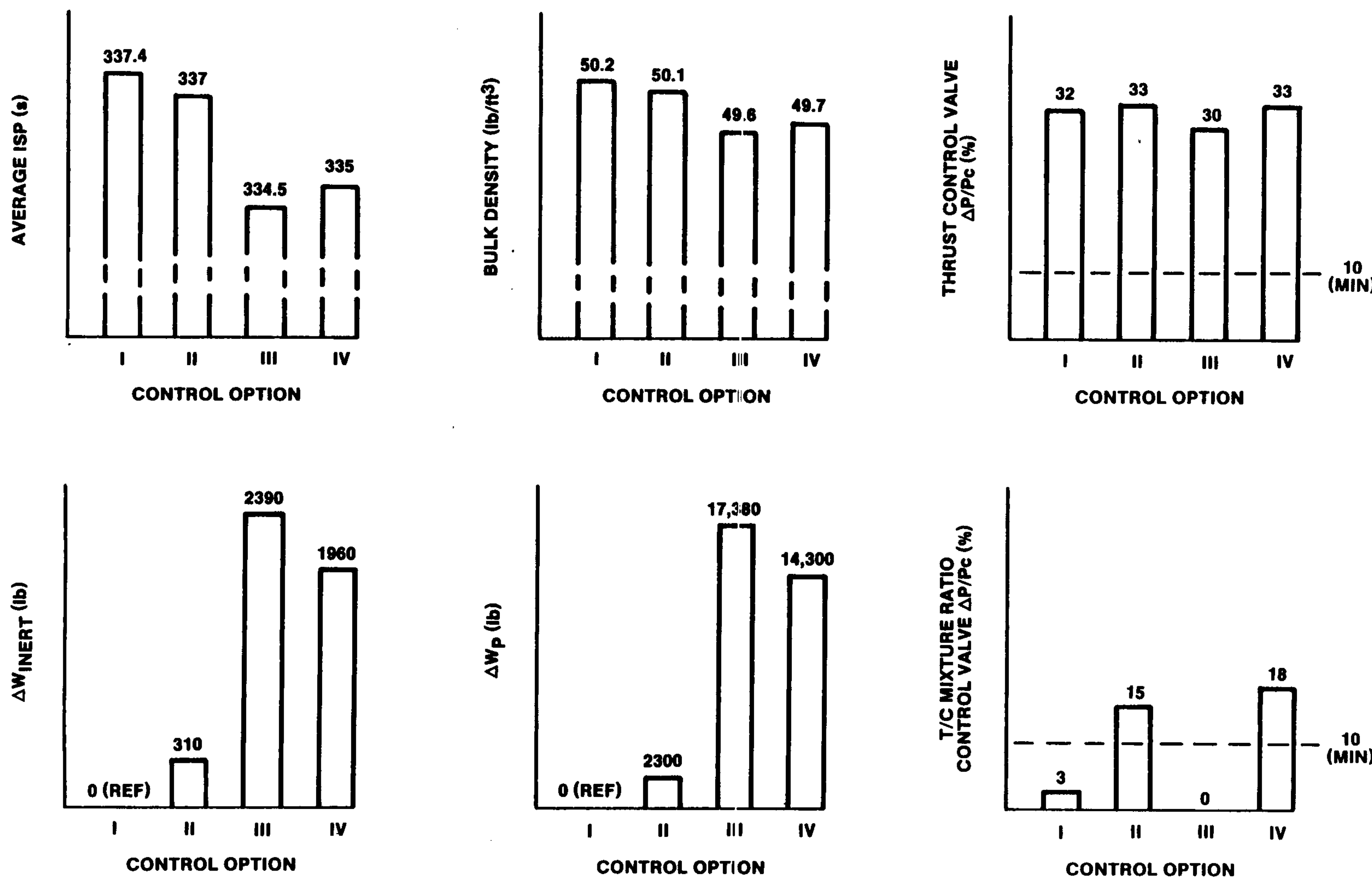
EFFECT OF CONTROL OPTIONS ON ENGINE 3, LOX/CH_4, CH_4 COOLED WITH T/C MIXTURE RATIO CONTROL

THIS CHART ILLUSTRATES THE EFFECT OF DIFFERENT THRUST AND MIXTURE RATIO CONTROL OPTIONS ON THE FUEL-COOLED LOX/CH_4 ENGINES AT THROTTLING CONDITION WITH CONSTANT T/C MIXTURE RATIO. IT SHOWS (CLOCK-WISE FROM TOP LEFT) THE AVERAGE SPECIFIC IMPULSE, PROPELLANT BULK DENSITY, THRUST CONTROL VALVE $\Delta P/Pc$ RATIO, T/C MIXTURE RATIO CONTROL VALVE $\Delta P/Pc$, TOTAL PROPELLANT CONSUMPTION AND VEHICLE INERT WEIGHT DIFFERENTIALS VS. THRUST AND T/C MIXTURE RATIO CONTROL OPTIONS.

CONTROL OPTION II WHICH RESULTS IN MINIMUM VEHICLE INERT WEIGHT DIFFERENTIAL WITH ADEQUATE VALVE ΔP MARGINS IS SELECTED FOR THE FUEL-COOLED LOX/CH_4 ENGINE. IN ADDITION, GG MIXTURE RATIO CONTROL IS RECOMMENDED FOR HIGH ENGINE PERFORMANCE.

EFFECT OF CONTROL OPTIONS ON ENGINE 3
LOX/CH_4, CH_4 COOLED
T/C MIXTURE RATIO CONTROL



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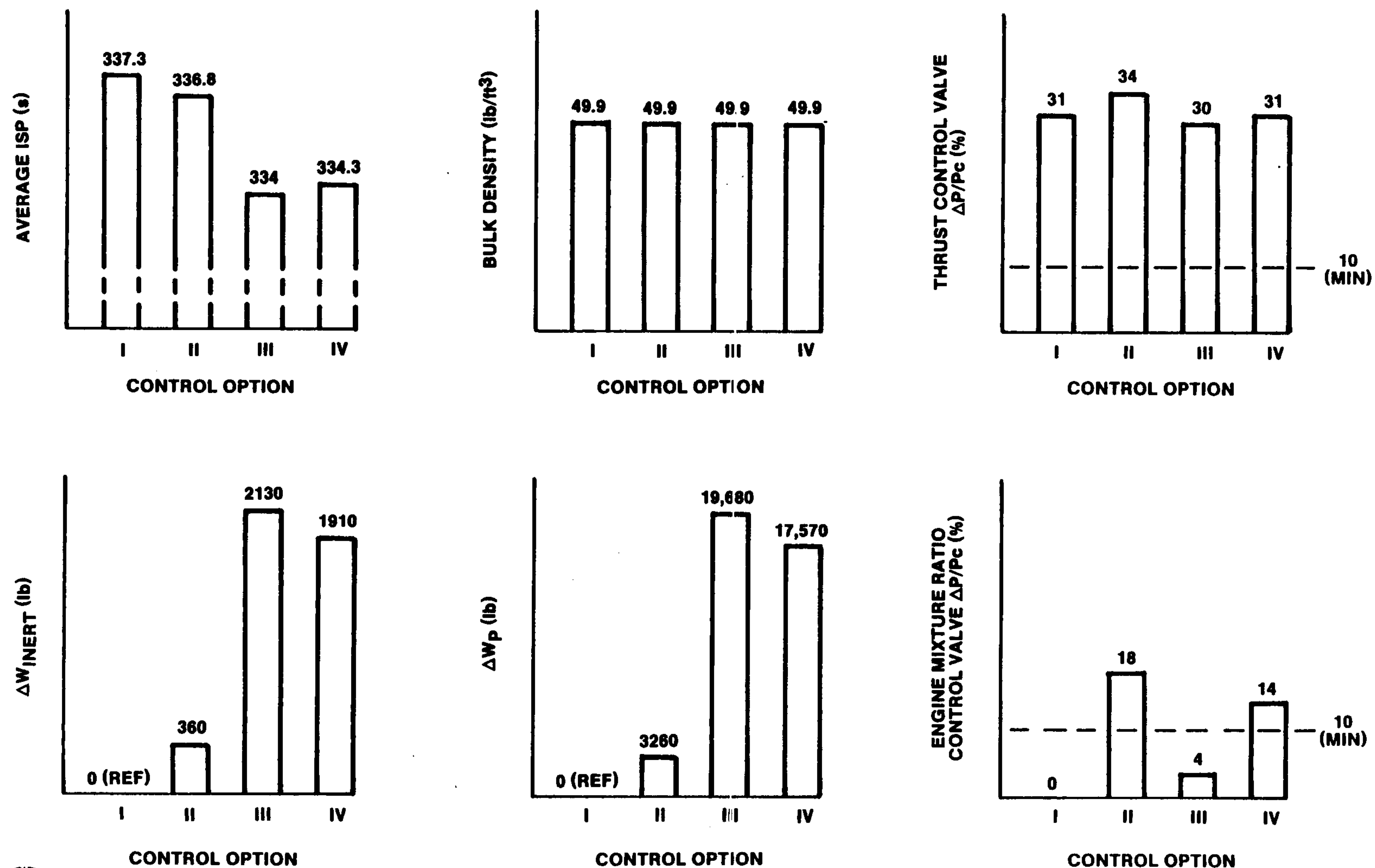
EFFECT OF CONTROL OPTIONS ON ENGINE 3, LOX/CH_4, CH_4 COOLED WITH ENGINE MIXTURE RATIO CONTROL

THIS CHART ILLUSTRATES THE EFFECT OF DIFFERENT THRUST AND MIXTURE RATIO CONTROL OPTIONS ON THE FUEL-COOLED LOX/CH_4 ENGINE AT THROTTLING CONDITION WITH CONSTANT ENGINE MIXTURE RATIO. IT SHOWS (CLOCK-WISE FROM TOP LEFT) THE AVERAGE SPECIFIC IMPULSE, PROPELLANT BULK DENSITY, THRUST CONTROL VALVE $\Delta P/Pc$ RATIO, ENGINE MIXTURE RATIO CONTROL VALVE $\Delta P/Pc$, TOTAL PROPELLANT CONSUMPTION AND VEHICLE INERT WEIGHT DIFFERENTIALS VS. THRUST AND ENGINE MIXTURE RATIO CONTROL OPTIONS.

CONTROL OPTION II WHICH RESULTS IN MINIMUM VEHICLE INERT WEIGHT DIFFERENTIAL WITH ADEQUATE VALVE ΔP MARGINS IS SELECTED FOR THE FUEL-COOLED LOX/CH_4 ENGINE. IN ADDITION, GG MIXTURE RATIO CONTROL IS RECOMMENDED FOR HIGH ENGINE PERFORMANCE.

EFFECT OF CONTROL OPTIONS ON ENGINE 3
LOX/CH_4, CH_4 COOLED
ENGINE MIXTURE RATIO CONTROL



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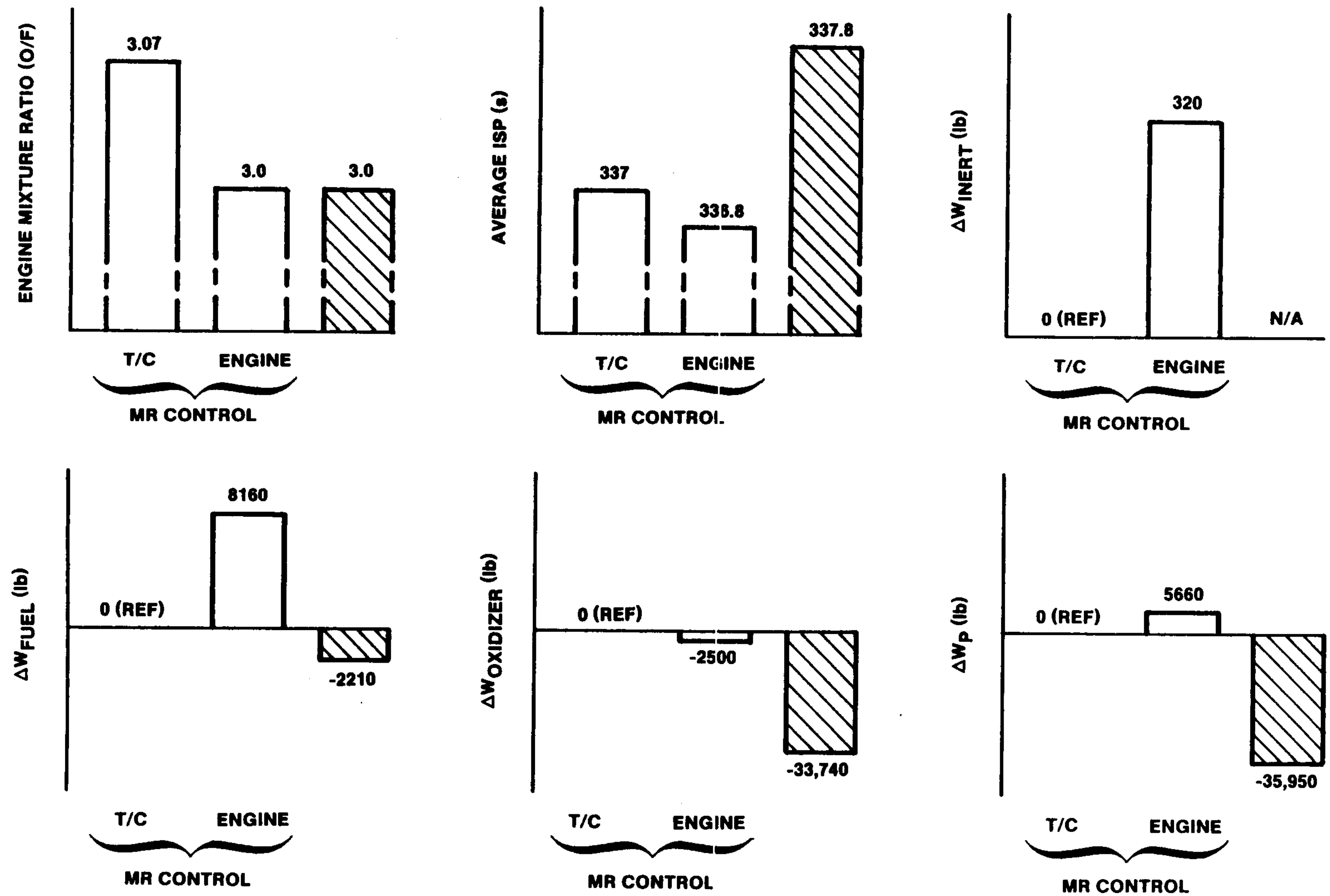
EFFECT OF T/C AND ENGINE MIXTURE RATIO CONTROL ON ENGINE 3 AT NOMINAL/OFF-NOMINAL CONDITIONS WITH SELECTED CONTROL OPTION II

THIS CHART ILLUSTRATES THE EFFECT OF T/C AND MIXTURE RATIO CONTROLS ON THE FUEL-COOLED LOX/CH_4 ENGINE AT NOMINAL AND OFF-NOMINAL OPERATING CONDITIONS. IT SHOWS (CLOCK-WISE FROM TOP LEFT) ENGINE MIXTURE RATIO, AVERAGE SPECIFIC IMPULSE, VEHICLE INERT WEIGHT DIFFERENTIAL, TOTAL PROPELLANT, LOX AND CH_4 CONSUMPTION DIFFERENTIALS VS. ENGINE OPERATING CONDITIONS AND MIXTURE RATIO CONTROLS. THE CONTROL OPTION II SELECTED PREVIOUSLY IS USED FOR THROTTLING; I.E., NOMINAL OPERATING CONDITION.

EFFECT OF T/C AND ENGINE MR CONTROL ON ENGINE 3 AT NOMINAL/OFF-NOMINAL CONDITIONS

CONTROL OPTION II



NOMINAL

OFF-NOMINAL

DN-55

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RESULTS/CONCLUSIONS

THESE ARE THE RESULTS AND CONCLUSIONS FROM THIS PRELIMINARY STEADY-STATE OFF-DESIGN STUDY CONDUCTED FOR THE FUEL-COOLED LOX/RP-1 AND LOX/CH_4 ENGINES.

RESULTS/CONCLUSIONS

- THROTTLING REQUIREMENTS ARE MET BY BOTH ENGINE CANDIDATES
- GG MIXTURE RATIO CONTROL RESULTS IN SIGNIFICANT BENEFIT ON ENGINE PERFORMANCE
- ENGINE PERFORMANCE WITH T/C MIXTURE RATIO CONTROL IS SLIGHTLY BETTER THAN THAT WITH ENGINE MIXTURE RATIO CONTROL
    - NEED ENGINE THRUST CONTROL
    - NEED T/C OR ENGINE MIXTURE RATIO CONTROL
    - RECOMMEND COOLANT FLOW SPLIT CONTROL
    - RECOMMEND GG MIXTURE RATIO CONTROL

RESULTS/CONCLUSIONS
(CONTINUED AND CONCLUDED)

THESE ARE THE THROTTLING VALVES RECOMMENDED FOR THE FUEL-COOLED LOX/RP-1 (ENGINE 1), LOX/C_3H_8 (ENGINE 2) AND LOX/CH_4 (ENGINE 3) ENGINES.

RESULTS/CONCLUSIONS
(CONTINUED)

- **SELECT CONTROL OPTION I FOR LOX/RP-1 ENGINE 1**
  - USE GGOV FOR THRUST CONTROL
  - USE MFV-2 FOR T/C OR ENGINE MIXTURE RATIO CONTROL
  - USE GGFV FOR GG MIXTURE RATIO CONTROL
  - USE MFV-1 FOR COOLANT FLOW SPLIT CONTROL

- **SELECT CONTROL OPTION II FOR LOX/C_3H_8 ENGINE 2 AND LOX/CH_4 ENGINE 3**
  - USE GGOV FOR THRUST CONTROL
  - USE MOV FOR T/C OR ENGINE MIXTURE RATIO CONTROL
  - USE GGFV FOR GG MIXTURE RATIO CONTROL
  - USE MFV-2 FOR COOLANT FLOW SPLIT CONTROL

STBE CONFIGURATION STUDY
SECOND QUARTERLY REVIEW
AGENDA

- INTRODUCTION .... F. KIRBY
- TASK 1 SUMMARY .... A. WEISS
- TASK 2 STATUS REVIEW
  - SUBSYSTEM OPTIMIZATION APPROACH .... A. WEISS
  - TURBOMACHINERY STUDIES .... A. EASTLAND
  - COMBUSTION DEVICES STUDIES .... P. MEHEGAN
  - THROTTLING ON-DESIGN/OFF-DESIGN STUDY .... W. BISSELL, D. NGUYEN
  - CONTROL SYSTEM AND HEALTH MONITOR STUDIES .... R. BREWSTER
- SUMMARY .... A. WEISS

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CONTROL AND CONDITION MAINTENANCE SYSTEM AGENDA

- OBJECTIVE/APPROACH
- REQUIREMENTS
- GROUND RULES
- COMPONENT CANDIDATES
- FINAL SELECTION APPROACH

STBE CONTROL AND CONDITION MAINTENANCE SYSTEM STUDIES

THIS CHART SUMMARIZES THE OBJECTIVE AND APPROACH TO CONDUCTING THE CONTROL AND CONDITION MAINTENANCE SYSTEM TRADE STUDIES. THE CONTROL SYSTEM ARCHITECTURE WILL BE COMMON TO ALL THE CONFIGURATIONS WHILE CERTAIN COMPONENT ELEMENTS WILL SERVE AS DISCRIMINATORS IN CHOOSING A OVERALL SYSTEM FOR EACH CONFIGURATION.

STBE CONTROL AND CONDITION MAINTENANCE SYSTEM STUDIES

- **OBJECTIVE**
  - SELECT OPTIMUM CONTROL SYSTEM CONFIGURATION FOR EACH CANDIDATE
- **APPROACH**
  - IDENTIFY REQUIREMENTS
  - IDENTIFY CANDIDATE SYSTEMS
    - GENERIC ARCHITECTURE
    - COMPONENT SELECTION
  - PERFORM LIFE CYCLE COST ANALYSIS TO SELECT OPTIMUM SYSTEM FOR EACH CANDIDATE

CONTROL AND CONDITION MAINTENANCE SYSTEM
PERFORMANCE CONTROL REQUIREMENTS

THE NEEDED CONTROL AND CONDITION MAINTENANCE SYSTEM FUNCTIONS ARE DRAWN FROM REQUIREMENTS DERIVED FROM ENGINE LEVEL REQUIREMENTS. THIS CHART SHOWS THE PERFORMANCE CONTROL PARAMETERS.

CONTROL AND CONDITION MAINTENANCE SYSTEM
PERFORMANCE CONTROL REQUIREMENTS

PARAMETER	ENGINE REQUIREMENT	CONTROL SYSTEM REQUIREMENT	CONTROL SYSTEM FUNCTIONS
THRUST	625 KLB OR 750 KLB	THRUST CONTROL, ACCURACY	•CLOSED LOOP CONTROL
MIXTURE RATIO	TBD ± 1.0%	MR CONTROL, ACCURACY	•PROPELLANT FLOW CONTROL
COOLANT FLOW	COOLANT FLOW SPLIT	COOLANT CONTROL	•FEEDBACK CAPABILITY
START	THRUST BUILDUP RATE, TIME	CONTROL RESPONSE, ACCURACY	•SYSTEM INTELLIGENCE
THROTTLING	MAX UPTHRUST RATE	CONTROL RESPONSE, ACCURACY	•HIGH ORDER LANGUAGE
SHUTDOWN	THRUST DECAY RATE, TIME, FAILSAFE	CONTROL RESPONSE, ACCURACY	
CONTROL SYSTEM	FAIL-OP, FAILSAFE	REDUNDANCY MANAGEMENT	

CONTROL AND CONDITION MAINTENANCE SYSTEM
CONDITION MAINTENANCE REQUIREMENTS

THE CONDITION MAINTENANCE REQUIREMENTS LEAD TO FUNCTIONS WHICH WILL DETERMINE HARDWARE HEALTH AND MAINTENANCE REQUIREMENTS RATHER THAN RELYING ON HARDWARE INSPECTION.

CONTROL AND CONDITION MAINTENANCE SYSTEM

CONDITION MAINTENANCE REQUIREMENTS

PARAMETER	ENGINE REQUIREMENT	CONTROL SYSTEM REQUIREMENT	CONTROL SYSTEM FUNCTION
GROUND SERVICING	NO SERVICING WITHIN 24 HOURS OF LOADING	MINIMIZE PRE-LAUNCH SERVICING	• INSTRUMENTATION
PRE-START CONDITIONING	NO EXTERNAL REDLINES	SELF MONITORING, ENGINE READY SIGNAL	• PERFORMANCE • DIRECT
START	ONE START WITHOUT RESERVICE	EXPENDIBLE IGNITERS	
DIAGNOSTICS	SELF DIAGNOSTIC	SELF TEST, MAINTENANCE DATA, REDLINE MONITORING	•EXPERT SYSTEM •DIAGNOSTICS •PROGNOSTICS
LIFE	100 MISSIONS	HARDWARE CONDITION MONITORING	
RELIABILITY	25 MISSIONS TO OVERHAUL		

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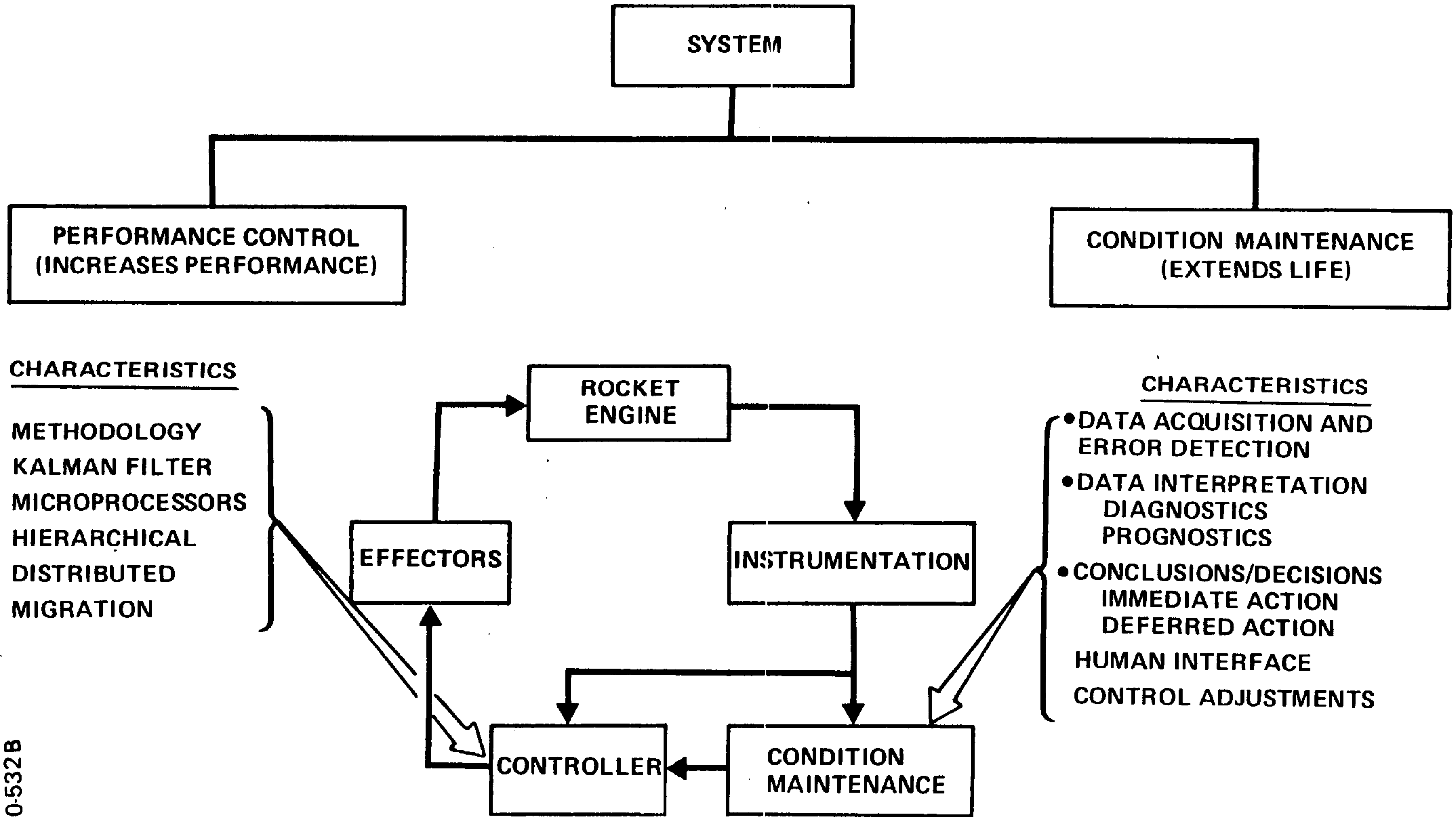
CONTROL AND CONDITION MAINTENANCE SYSTEM PHILOSOPHY

THE OVERALL SYSTEM DESIGN PHILOSOPHY WILL BE A CLOSED LOOP SYSTEM WITH PERFORMANCE CONTROL AND CONDITION MAINTENANCE ASPECTS.

CONTROL AND CONDITION MAINTENANCE SYSTEM PHILOSOPHY



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CONTROL AND CONDITION MAINTENANCE SYSTEM
GROUNDRULES

THIS CHART REFLECTS THE TECHNOLOGY LEVELS FOR THE 1985 AND 2000 ENGINES. THE ADVANTAGES OF THESE TECHNOLOGIES ARE SHOWN FOR EACH OF THE MAJOR SYSTEM FEATURES.

CONTROL AND CONDITION MAINTENANCE SYSTEM
GROUNDRULES

FEATURES	1995	2000	ADVANTAGE
CLOSED LOOP CONTROL PHILOSOPHY	DIGITAL/MULTI-VARIABLE/ OPTIMAL	DIGITAL/MULTI-VARIABLE/ ADAPTIVE	OPTIMIZED PERFORMANCE CONTROL
SOFTWARE LANGUAGE	HIGH ORDER	HIGH ORDER	REDUCED MAINTENANCE
EXPERT SYSTEMS	DEFERRED	ACTIVE	ENHANCED FAILURE DETECTION REDUCED MAINTENANCE
PROPELLANT FLOW CONTROL	ELECTRIC/HYDRAULIC	ELECTRIC	REDUCED SYSTEM COMPLEXITY IMPROVED MAINTAINABILITY
INSTRUMENTATION	PERFORMANCE	DIRECT MEASUREMENT	ENHANCED FAILURE DETECTION REDUCED MAINTENANCE
MICROPROCESSOR TECHNOLOGY	32 BIT	PARALLEL PROCESSORS	INCREASED PARAMETER THROUGHPUT
INTERCONNECTS	COPPER	FIBER OPTIC	IMPROVED SIGNAL CAPABILITY DECREASED WEIGHT

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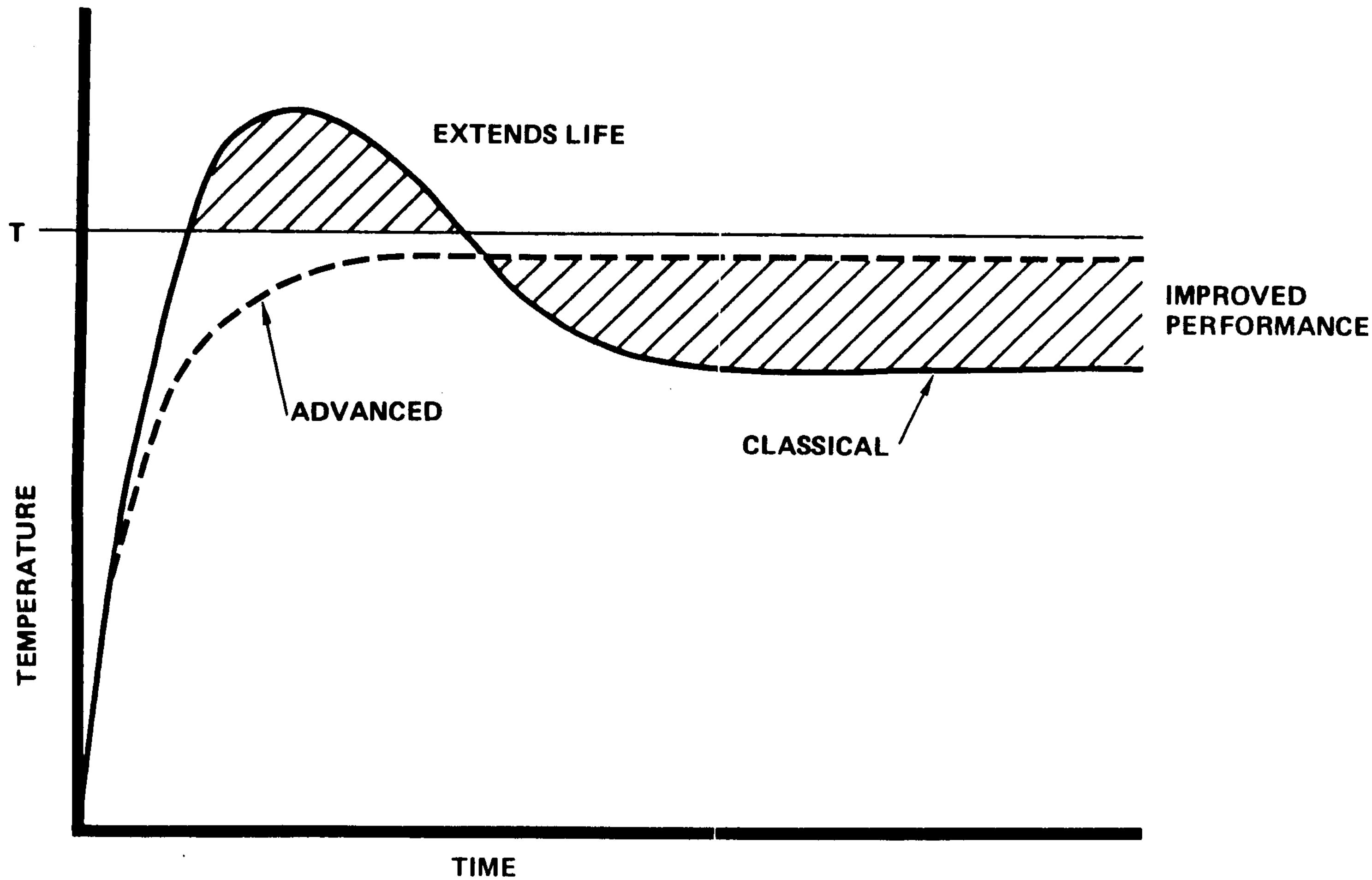
ADVANCED CONTROL EXTENDS LIFE AND IMPROVES PERFORMANCE

THIS CHART SHOWS HOW ADVANCED CONTROL TECHNIQUES CAN MORE CLOSELY CONTROL TO A GIVEN REQUIREMENT WHICH IMPROVES SYSTEM PERFORMANCE AND CAN INCREASE LIFE.

ADVANCED CONTROL EXTENDS LIFE AND IMPROVES PERFORMANCE



700-559A

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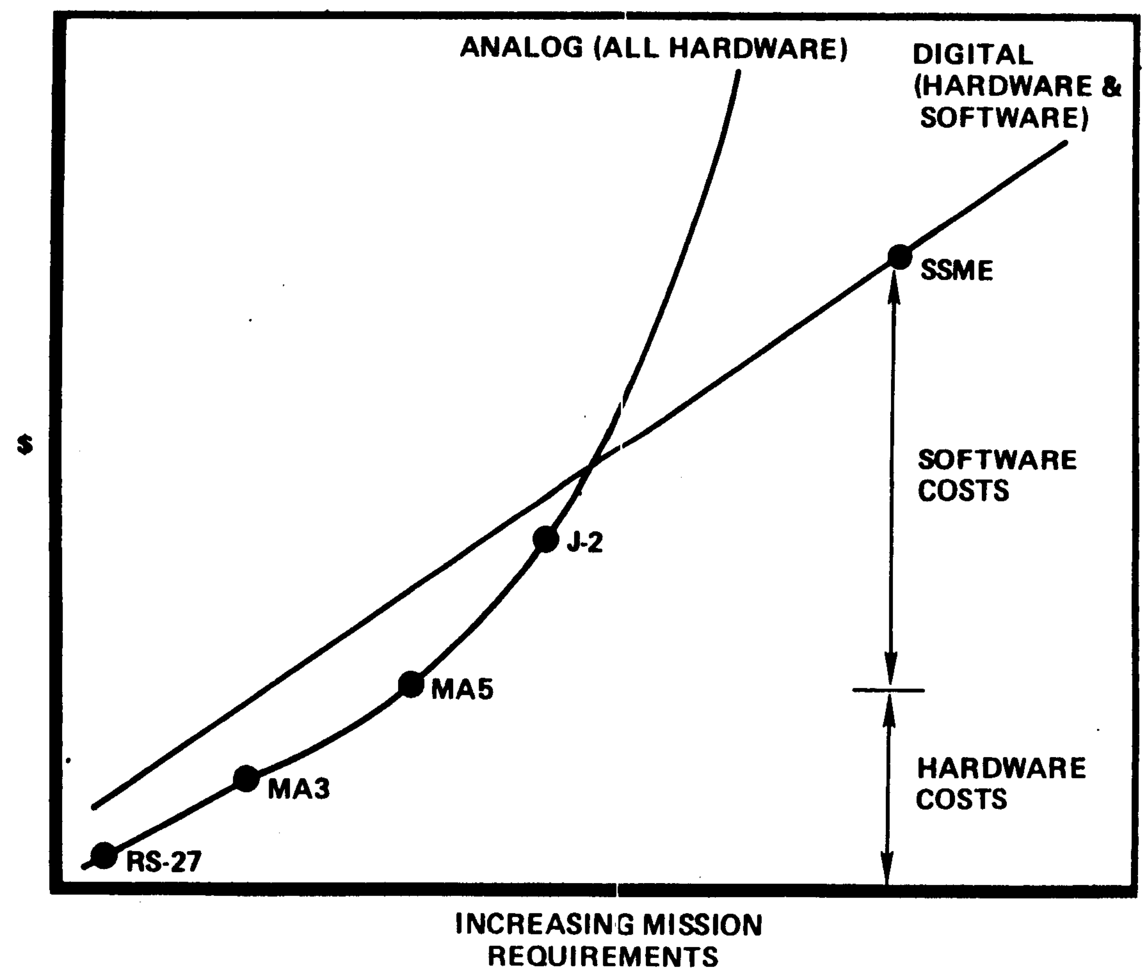
CONTROL SYSTEM FUNCTIONAL CAPABILITY vs COST

THE CAPABILITY REQUIRED OF AN ANALOG CONTROL SYSTEM MAKES IT COST PROHIBITIVE AS SHOWN BY THE EXPERIENCE CURVE. A DIGITAL SYSTEM HAS MORE FLEXIBILITY TO MEET MORE REQUIREMENTS FOR THE SAME COST.

CONTROL SYSTEM FUNCTIONAL CAPABILITY vs.COST



412-432B

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CONTROL METHODOLOGY/IMPLEMENTATION COMPARISON

THE POSSIBLE CONTROL METHODOLOGIES FOR USE ON THE STBE ARE SHOWN ON THIS CHART. A DIGITAL SYSTEM WILL BE REQUIRED TO TAKE ADVANTAGE OF THE ADVANCED OPTIMAL AND ADAPTIVE TECHNIQUES.

CONTROL METHODOLOGY/IMPLEMENTATION COMPARISON

<table>
<tr><td>CONTROL METHODOLOGY</td><td colspan="2">CLASSICAL</td><td colspan="3">MODERN</td></tr>
<tr><td>CONTROL APPLICATION</td><td>OPEN/CLOSED LOOP</td><td>MULTIVARIABLE</td><td>OPTIMAL</td><td>ADAPTIVE</td><td>LEARNING</td></tr>
<tr><td>IMPLEMENTATION</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>MECHANICAL</td><td>ANALOG</td><td></td><td></td><td></td><td></td></tr>
<tr><td>HYDRAULIC</td><td colspan="2">ANALOG</td><td></td><td></td><td></td></tr>
<tr><td>PNEUMATIC</td><td colspan="2">ANALOG</td><td></td><td></td><td></td></tr>
<tr><td>ELECTRIC</td><td colspan="3">ANALOG & DIGITAL</td><td colspan="2">DIGITAL</td></tr>
<tr><td>FLUIDIC</td><td colspan="3">ANALOG & DIGITAL</td><td></td><td></td></tr>
</table>

298-255B

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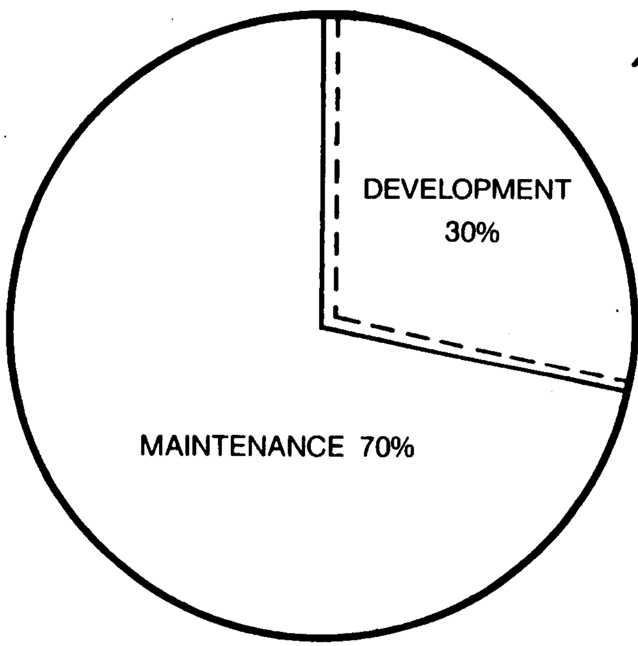
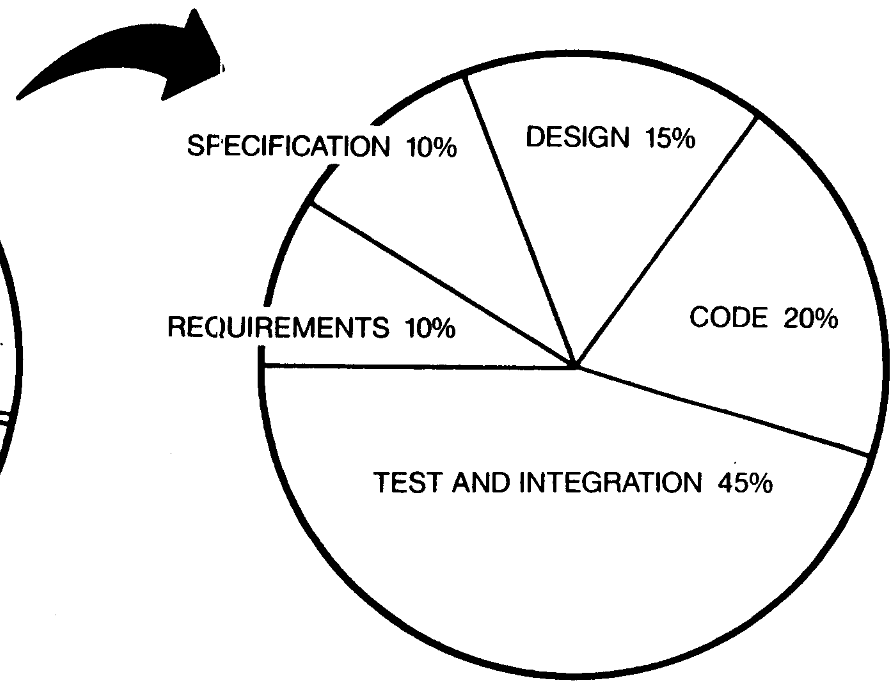
SOFTWARE DEVELOPMENT vs MAINTENANCE COSTS

THE CHART SHOWS WHY A HIGHER ORDER SOFTWARE LANGUAGE IS NECESSARY. SINCE MAINTENANCE IS 70% OF THE LIFE CYCLE COST OF SOFTWARE, SUCH A LANGUAGE REDUCES THE EFFORT REQUIRED TO CHANGE OR CORRECT THE LOGIC.

SOFTWARE DEVELOPMENT vs MAINTENANCE COSTS



SOFTWARE OPERATIONAL
LIFE CYCLE



SOFTWARE DEVELOPMENT
LIFE CYCLE

86D-9-1992

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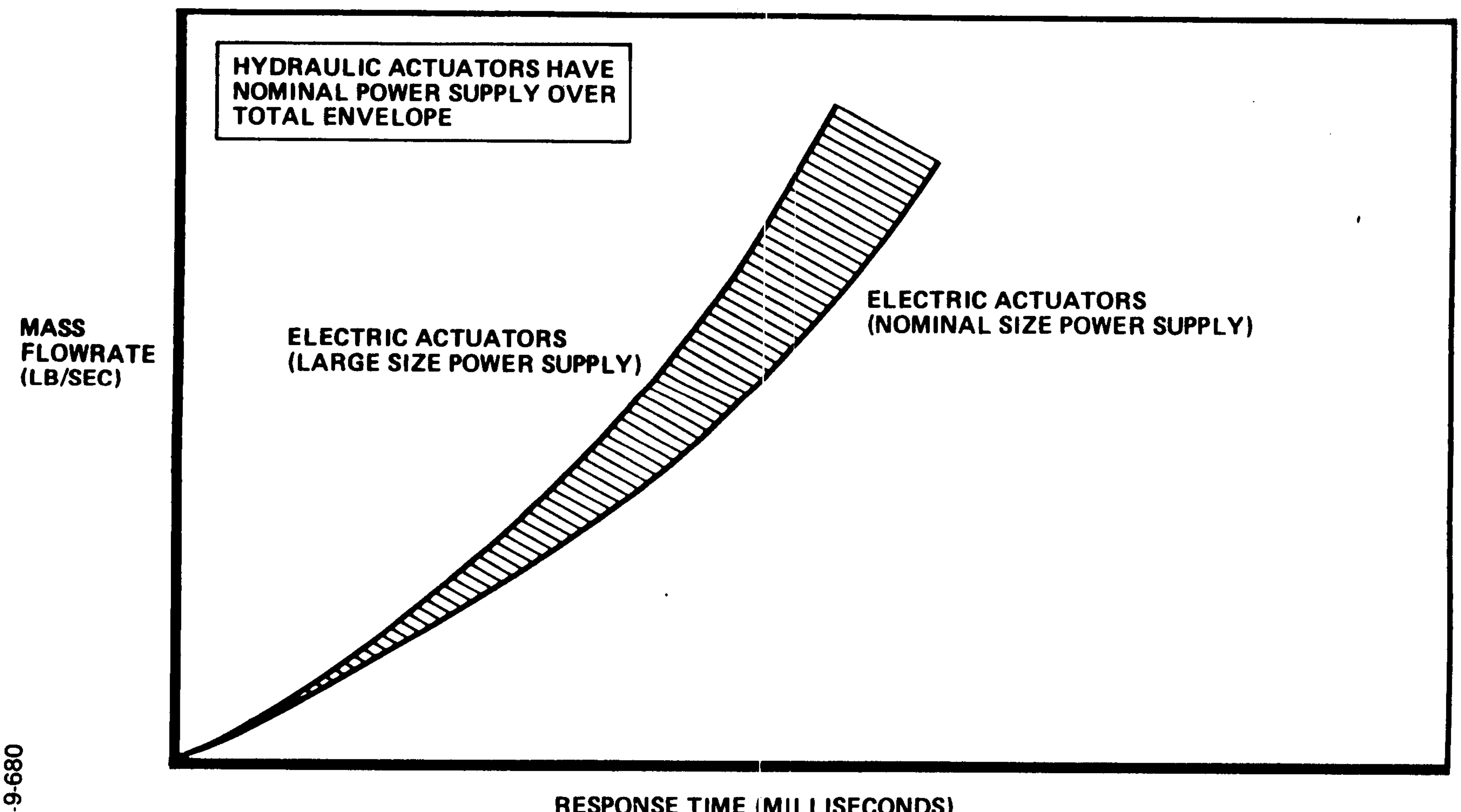
HYDRAULIC - ELECTRIC ACTUATOR OPERATING REGIMES

THIS FIGURE SHOWS THE OPERATING REGIMES FOR HYDRAULIC AND ELECTRIC ACTUATORS. ELECTRIC ACTUATORS HAVE DESIRABLE CHARACTERISTICS WHICH MAKE THEIR USE FOR THE STBE APPLICATION MORE ATTRACTIVE THAN HYDRAULIC ACTUATORS. THE FIGURE SHOWS THAT AS THE CONTROLLED FLUID MASS FLOWRATE INCREASES AND THE REQUIRED RESPONSE TIME DECREASES, THE SIZE OF THE REQUIRED ELECTRICAL POWER SUPPLY BECOMES VERY LARGE WHILE THE SIZE OF THE HYDRAULIC POWER SUPPLY REMAINS NOMINAL. A STUDY WILL BE MADE ON THE RELATIVE MERITS OF AN ALL HYDRAULIC SYSTEM VERSUS USING HYDRAULIC ACTUATION FOR LARGE MASS FLOWRATE/LOW RESPONSE TIME SYSTEMS AND AN ELECTRIC SYSTEM FOR LOWER MASS FLOWRATE/LONGER RESPONSE TIME SYSTEMS.

1 13

HYDRAULIC-ELECTRIC ACTUATOR OPERATING REGIMES

OPERATING POWER REQUIREMENTS



86C-9-680

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CONDITION MONITOR PARAMETER SUMMARY

CONDITION MAINTENANCE REQUIRES DIRECT MEASUREMENT OF KEY HARDWARE PARAMETERS. THIS CHART SHOWS EIGHT SUCH DIRECT MEASUREMENT TECHNOLOGIES UNDER DEVELOPMENT AT ROCKETDYNE. FOR EXAMPLE, THESE MEASUREMENTS WOULD ALLOW DELETION OF CERTAIN HARDWARE INSPECTIONS ON THE SSME.

CONDITION MONITOR PARAMETER SUMMARY

FAILURE MODE	HARDWARE AFFECTED	MEASUREMENT TECHNOLOGY							
		ISOTOPE	DEFLECTO-METER	TORQUE METER	PYRO-METER	ACOUSTO-OPTICAL	EXO ELECTRON	SPECTRO-METER	HOLO-GRAPHIC
WEAR	BEARINGS	X							
SPACING	BEARINGS		X						
RUBBING/ BINDING	BEARINGS, SEALS			X					
THERMAL STRESS	TURBINE BLADES				X				
CRACKING	TURBINE BLADES DISK, IMPELLERS					X			
FATIGUE	TURBINE BLADES, DISKS, IMPELLERS						X		
EROSION	INJECTORS, NOZZLES							X	
LEAKAGE	JOINTS, WELDS								X
COMPARABLE SSME INSPECTIONS ELIMINATED		SHAFT TRAVEL	BORE-SCOPE	TORQUE CHECK	22X MICRO-SCOPIC		REPLACE BY SCHEDULE	BORE-SCOPE	SOAP CHECK

86D-9-649A

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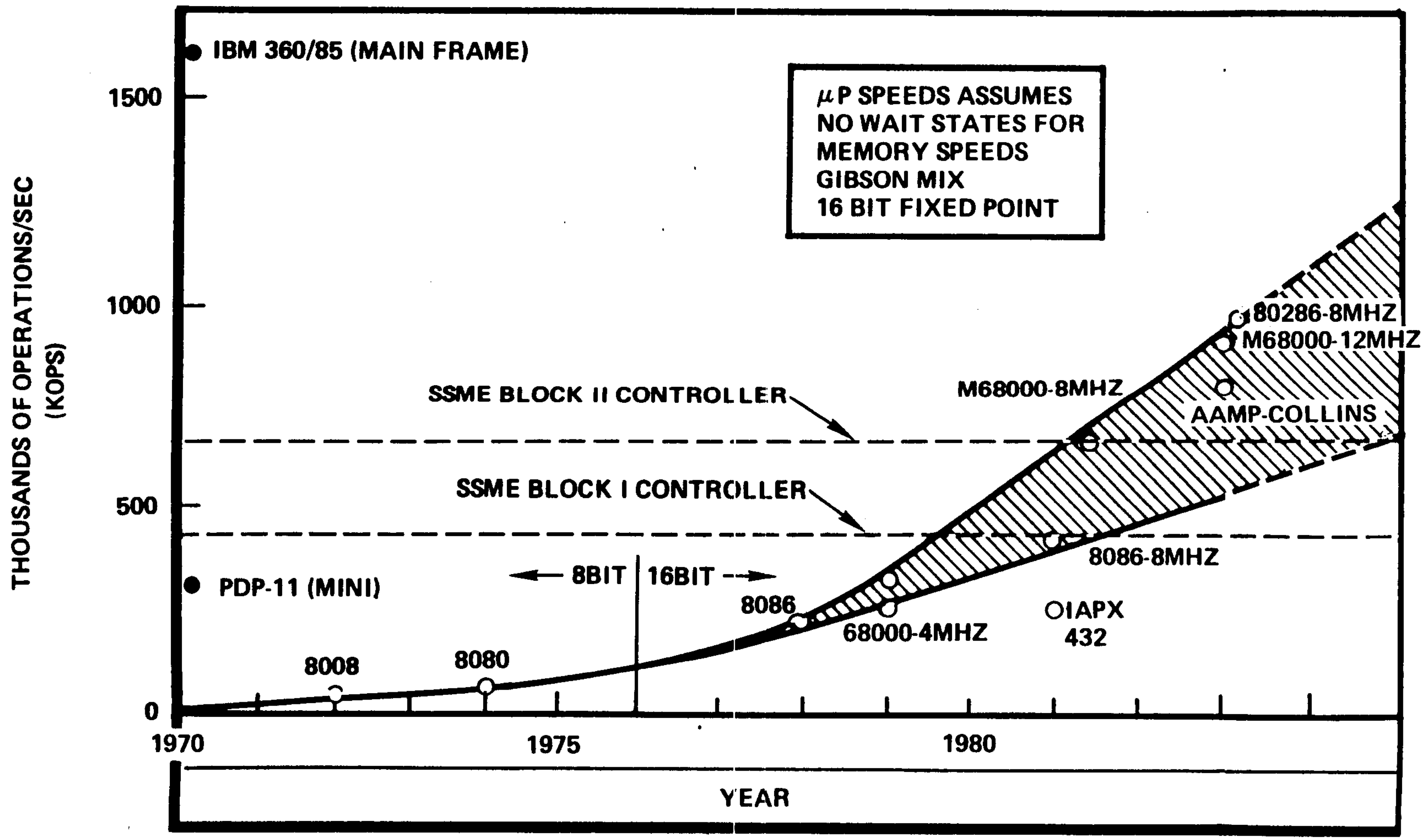
COMPUTING POWER (SPEED) OF MICRO-PROCESSORS HAS INCREASED RAPIDLY

AS ENGINES BECOME MORE COMPLEX THE NEED FOR FASTER CONTROL SYSTEMS TO CONTROL AND PROVIDE CONDITION MAINTENANCE FUNCTIONS DURING NORMAL AND ABNORMAL OPERATIONAL CONDITIONS HAS ALSO INCREASED.

IN THE EARLY 1970'S THE INITIAL MICRO-PROCESSORS WERE 8 BIT MACHINES. WITH THE ADVENT OF 16 BIT MACHINES IN THE LATE 1970'S COMPUTING POWER INCREASED 3 TO 10 TIMES. WITH THE INTRODUCTION OF 32 BIT MICRO-PROCESSORS IN 1984, SUCH AS THE M68020 AND THE 80386-20 MHZ, COMPUTING POWER HAS INCREASED ANOTHER 3 TO 5 TIMES OVER THE 16 BIT M68000-12 MHZ AND 80286-8MHZ MICRO-PROCESSORS. THIS INCREASED COMPUTING POWER ALLOWS MODERN CONTROL AND CONDITION MAINTENANCE SYSTEMS TO BE IMPLEMENTED IN AN EFFECTIVE AND EFFICIENT MANNER FOR INCREASED ENGINE SYSTEM EFFECTIVENESS.

COMPUTING POWER (SPEED) OF MICRO-PROCESSORS HAS INCREASED RAPIDLY



297-483F

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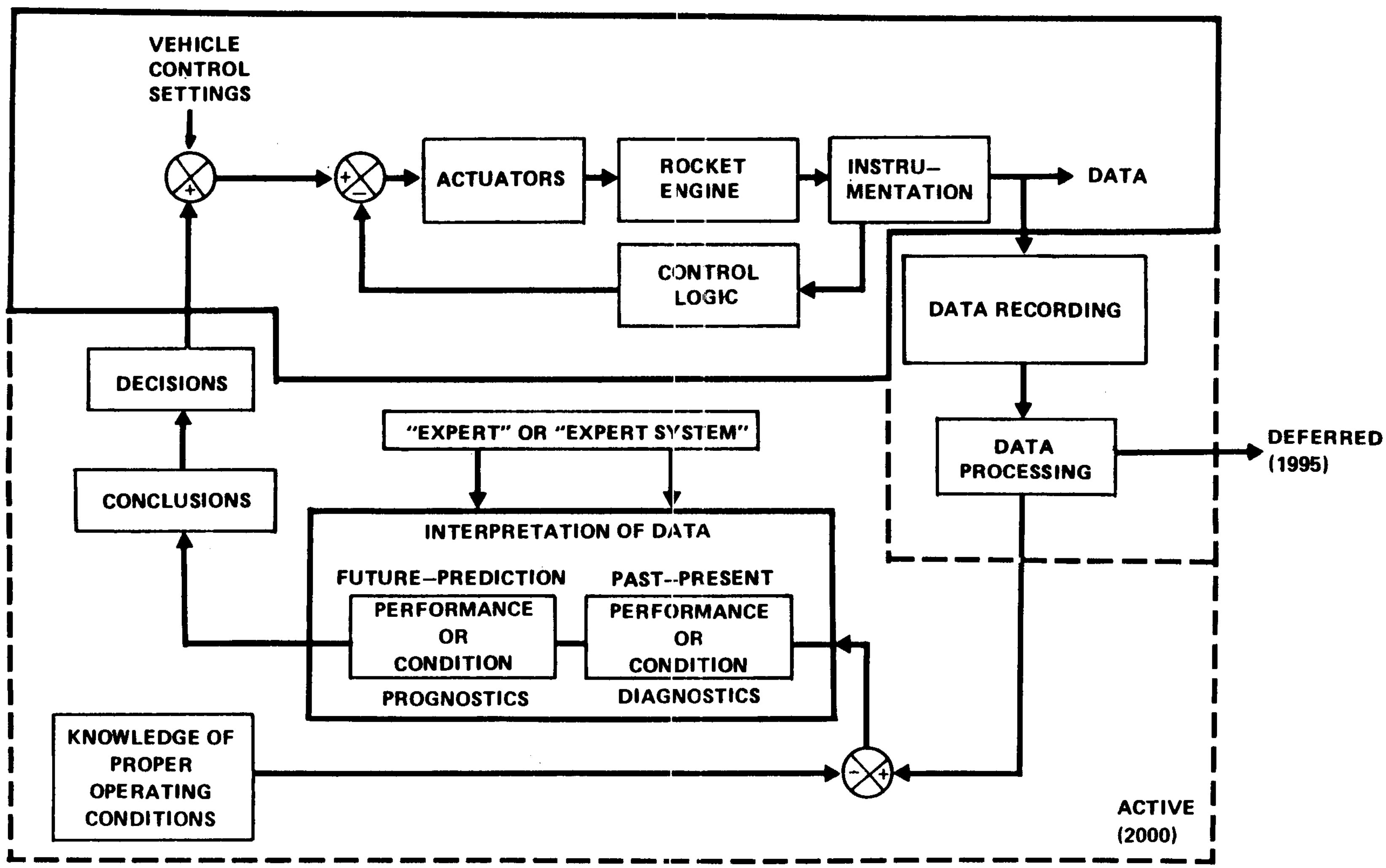
CONTROL AND CONDITION MAINTENANCE SYSTEM
1995 vs 2000 CONFIGURATION

THE CONTROL AND CONDITION MAINTENANCE SYSTEM TOP LEVEL SCHEMATIC IS SHOWN ON THIS CHART. THE BASIC CLOSED LOOP CONTROL PORTION IS SHOWN INSIDE THE BLACK BORDER. THE CONDITION MAINTENANCE PORTION FOR BOTH THE 1995 AND 2000 ENGINES IS ALSO SHOWN. THIS BASELINE SYSTEM WILL BE COMMON TO ALL THE STBE CANDIDATE CONFIGURATIONS.

CONTROL AND CONDITION MAINTENANCE SYSTEM

1995 vs 2000 CONFIGURATION



86C-9-251A

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CONTROL SYSTEM SENSITIVITY RESULTS

THESE ARE THE RESULTS OF THE CONTROL SENSITIVITY STUDY. THEY DEFINE REQUIREMENTS FOR WHICH CONTROL LOOPS ARE NEEDED AND WHICH VALVES HAVE TO BE CONTROLLED.

CONTROL SYSTEM SENSITIVITY RESULTS

- **SELECT CONTROL OPTION I FOR LOX/RP-1 ENGINE 1**
  - USE GGOV FOR THRUST CONTROL
  - USE MFV-2 FOR T/C OR ENGINE MIXTURE RATIO CONTROL
  - USE GGFV FOR GG MIXTURE RATIO CONTROL
  - USE MFV-1 FOR COOLANT FLOW SPLIT CONTROL

- **SELECT CONTROL OPTION II FOR LOX/C_3H_8 ENGINE 2 AND LOX/CH_4 ENGINE 3**
  - USE GGOV FOR THRUST CONTROL
  - USE MOV FOR T/C OR ENGINE MIXTURE RATIO CONTROL
  - USE GGFV FOR GG MIXTURE RATIO CONTROL
  - USE MFV-2 FOR COOLANT FLOW SPLIT CONTROL

1995 CONTROL AND CONDITION MAINTENANCE DISCRIMINATORS

THE CONTROL AND CONDITION MAINTENANCE (CCM) COMPONENTS HAVE BEEN EVALUATED TO ESTABLISH HOW THEIR CHARACTERISTICS RELATE TO THE 1995 ENGINE CANDIDATES. AS A RESULT OF THIS EVALUATION, THE PRIMARY CCM COMPONENTS THAT WERE FOUND TO BE AFFECTED (DISCRIMINATED) BY THE CANDIDATE ENGINES ARE THE CCM CONTROL LOOPS, INSTRUMENTATION, VALVES AND ACTUATORS. THE EFFECT OF EACH OF THE ENGINE CANDIDATES ON EACH OF THESE CCM DISCRIMINATORS WILL BE DETERMINED TO DEFINE THE CCM SYSTEMS AFFECTS ON THE SELECTION OF THE 1995 ENGINE SYSTEM.

1995 CONTROL AND CONDITION MAINTENANCE DISCRIMINATORS

ELEMENT	ENGINE 1	2	3	4	5	6	11	12	18
CONTROL LOOPS — QUANTITY	4	4	4						
INSTRUMENTATION — QUANTITY • PERFORMANCE • CONDITION MONITOR									
VALVES • QUANTITY • TYPE									
ACTUATORS • QUANTITY • TYPE									
START SEQUENCE • TYPE • PROPELLANT CONSUMPTION									

86D-9-1991

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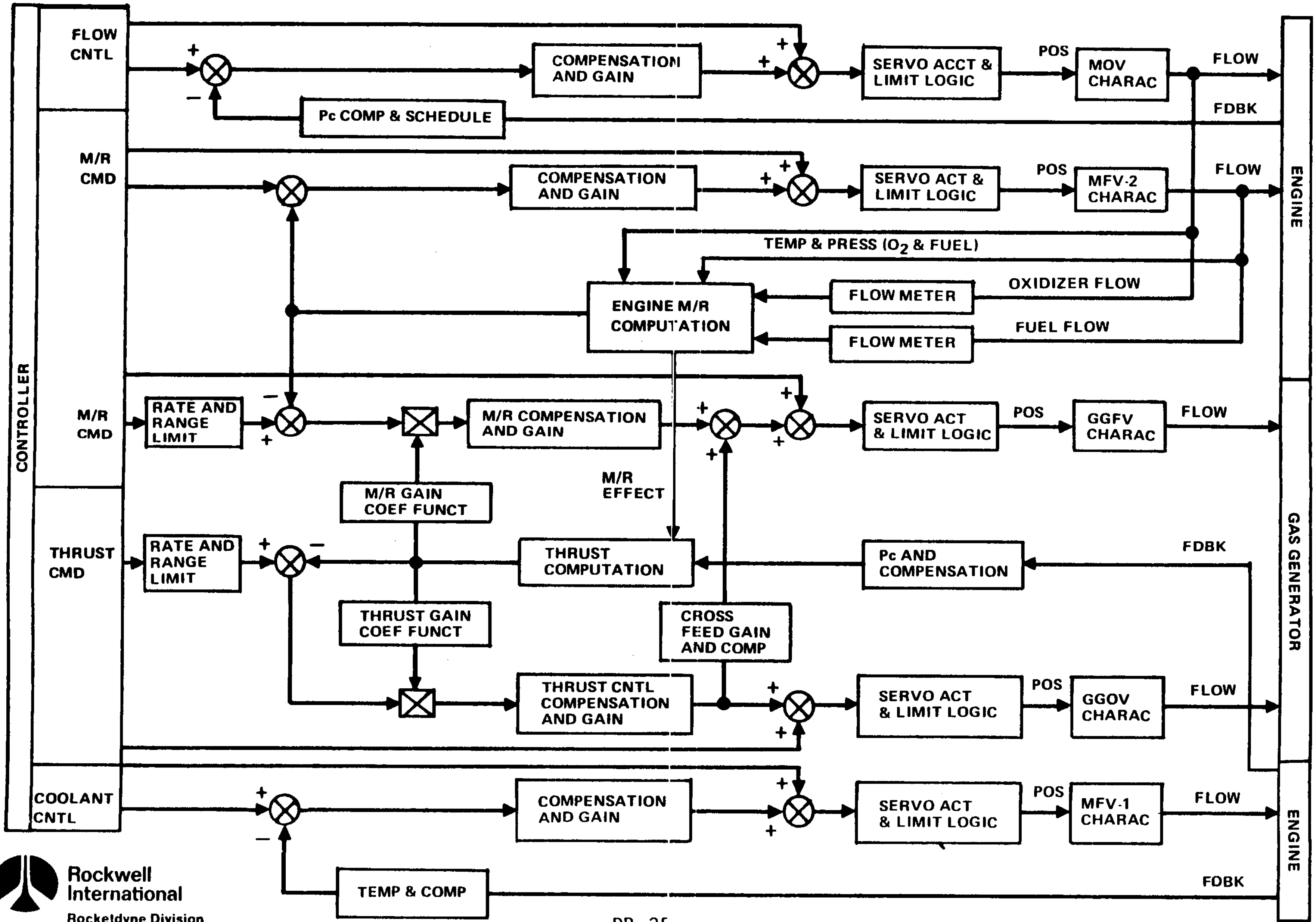
1995 STBE CLOSED LOOP CONTROL DIAGRAM

THIS DIAGRAM SHOWS THE BE-1 ENGINE CONTROL LOOPS AND THEIR INTERFACES WITH THE CONTROLLER. THE RELATIONSHIP AND FUNCTIONS OF THE INSTRUMENTS AND ACTUATOR/VALVES ARE SHOWN TOGETHER WITH THE LOGIC FUNCTION THAT MUST BE PERFORMED. SIMILAR DIAGRAMS OF EACH ENGINE CANDIDATE WILL LEAD TO QUANTIFICATION OF THE CCM DISCRIMINATORS FOR SELECTION OF THE 1995 BASELINE ENGINE.

18

1995 STBE CLOSED-LOOP CONTROL DIAGRAM
ENGINE 1



86C-9-671

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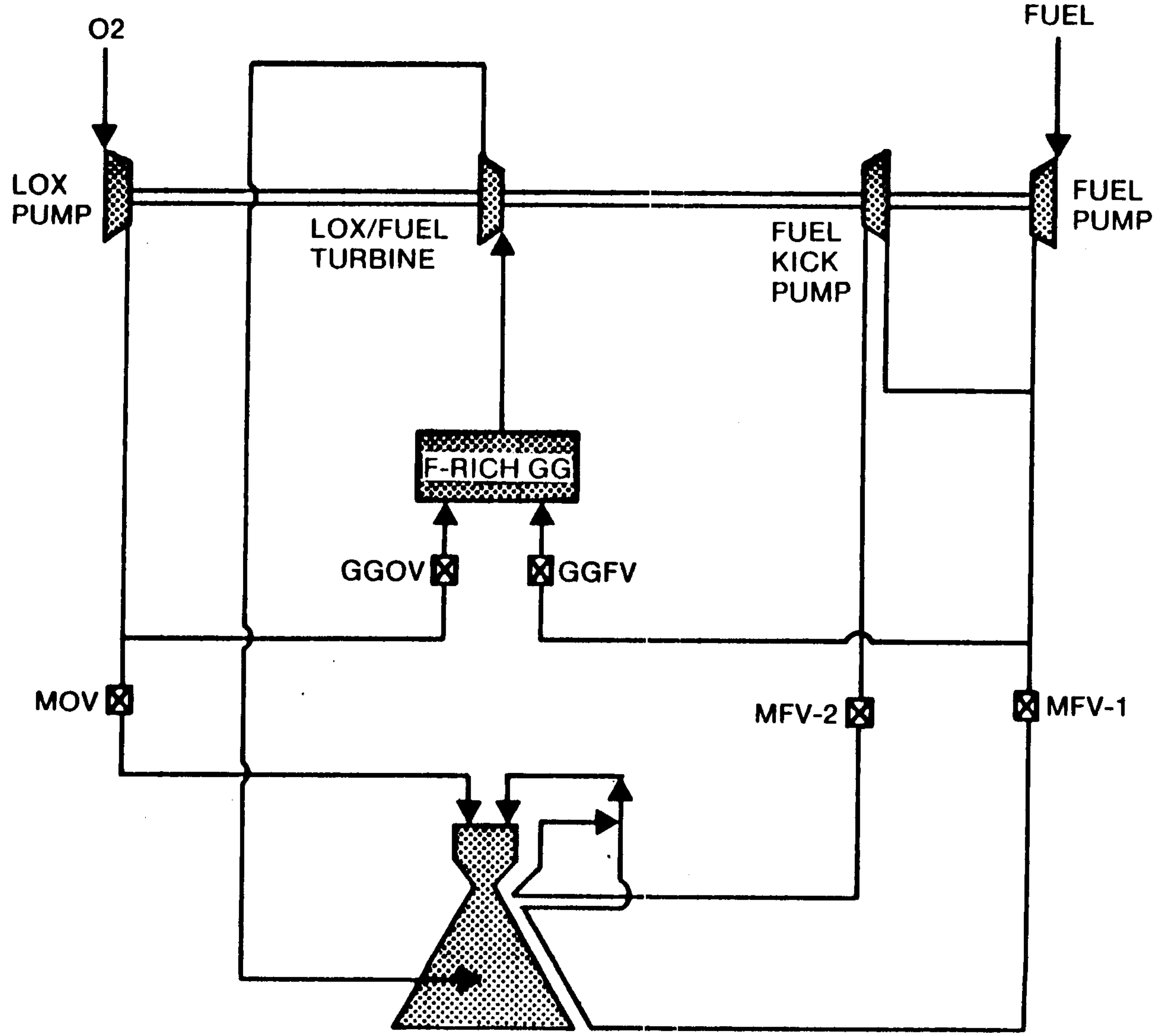
ENGINE 1 FLOW SCHEMATIC
LOX/RP-1, RP-1 COOLED

THIS SCHEMATIC OF THE LOX/RP-1, RP-1 COOLED ENGINE SHOWS THE LOCATION OF THE PROPELLANT VALVES. THE SCHEMATIC ALSO AIDS IN DETERMINING WHAT PARAMETERS MAY HAVE TO BE MEASURED TO OPERATE EACH OF THE CONTROL LOOPS.

ENGINE 1 FLOW SCHEMATIC
LOX/RP-1, RP-1 COOLED



86D-9-1854

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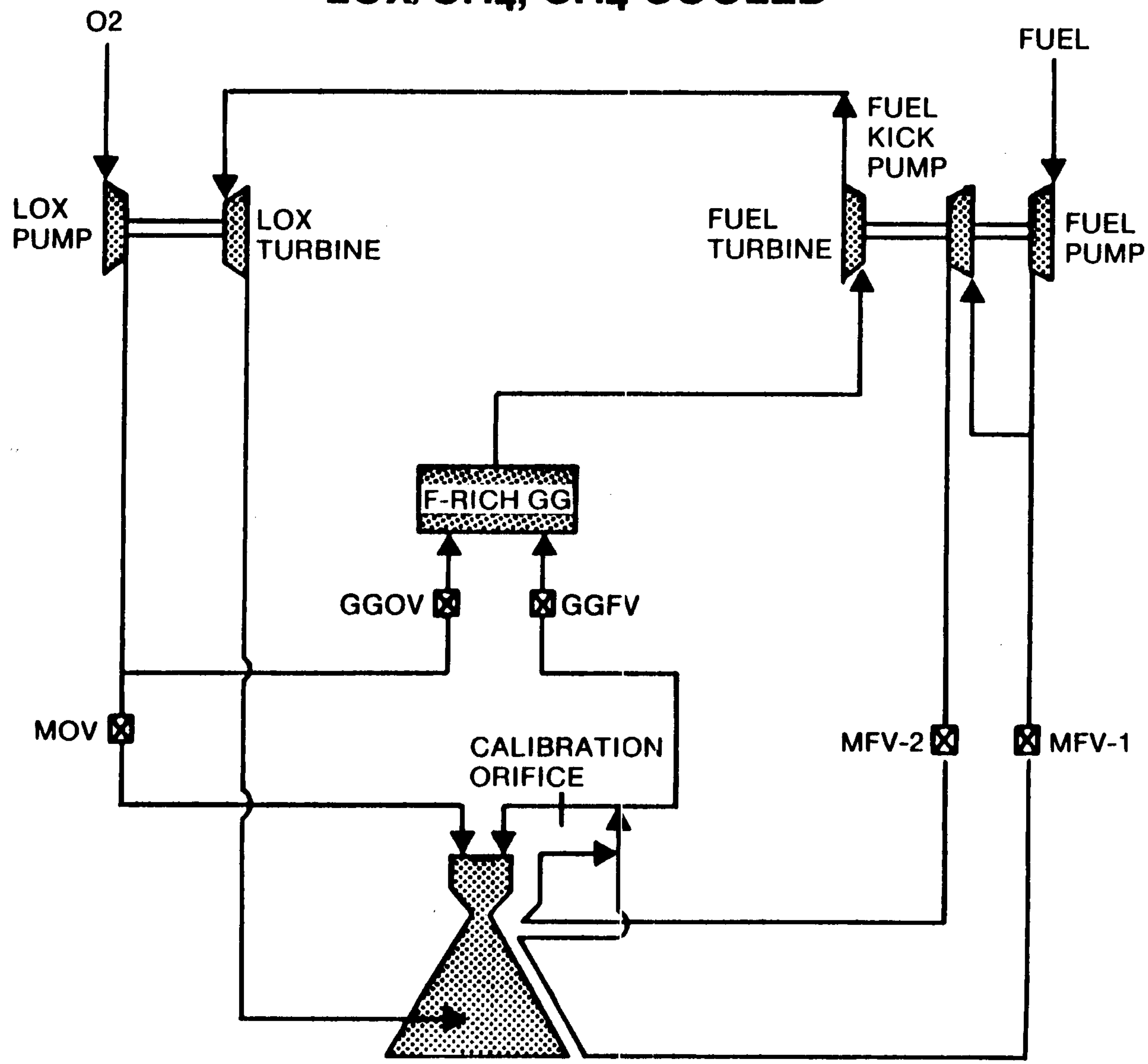
ENGINE 3 FLOW SCHEMATIC
LOX/CH_4, CH_4 COOLED

THIS IS THE SCHEMATIC OF THE LOX/METHANE, METHANE COOLED ENGINE. THE LOX/CH_3H_8 COOLED ENGINE ALSO HAS THE SAME SCHEMATIC.

ENGINE 3 FLOW SCHEMATIC
LOX/CH_4, CH_4 COOLED



86D-9-1855

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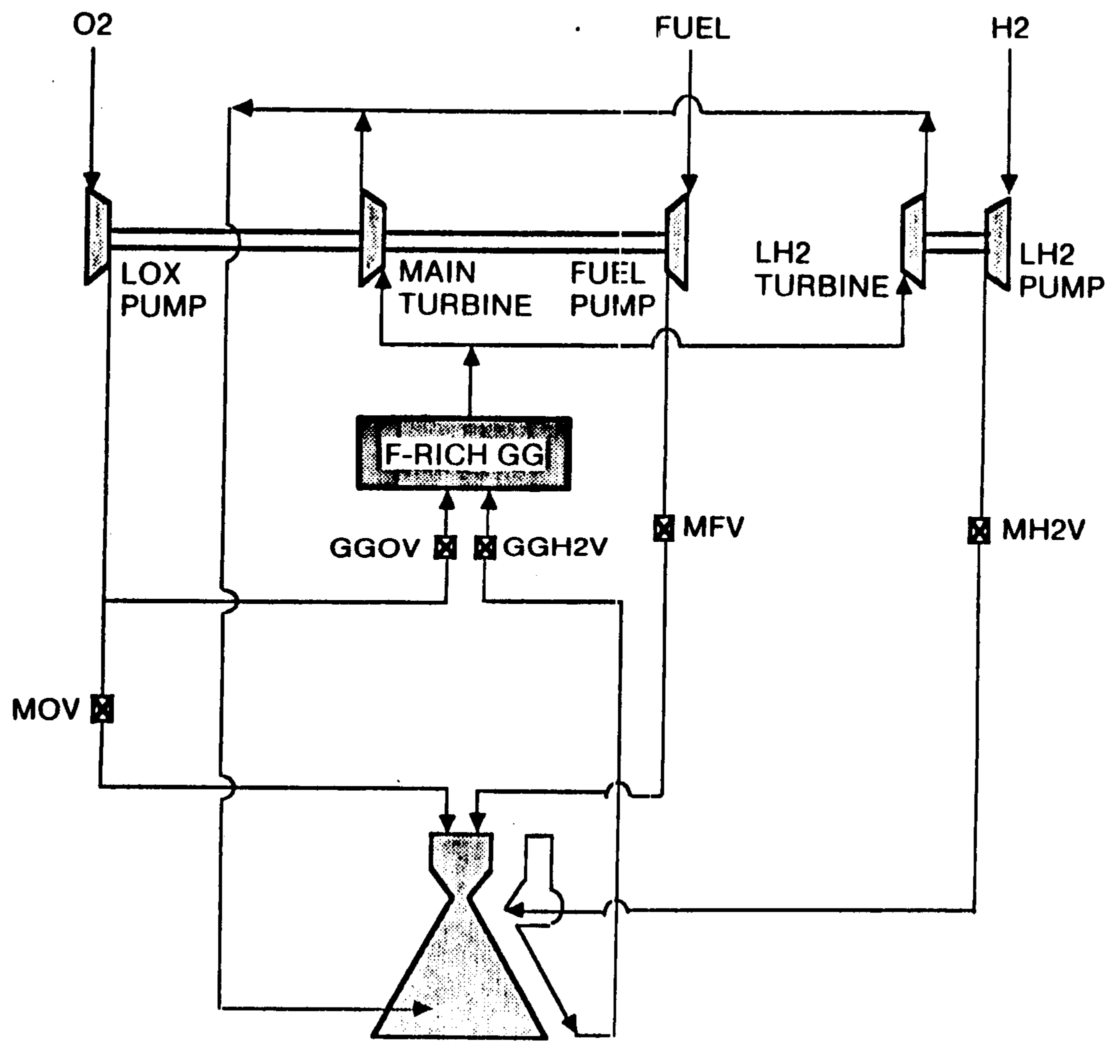
LH_2 COOLED ENGINE FLOW SCHEMATIC
ENGINES 4, 5, AND 6

THIS SCHEMATIC COVERS THE THREE ENGINES WHICH ARE HYDROGEN COOLED.

LH2-COOLED ENGINE FLOW SCHEMATIC

ENGINES 4, 5, AND 6



86D-9-1972

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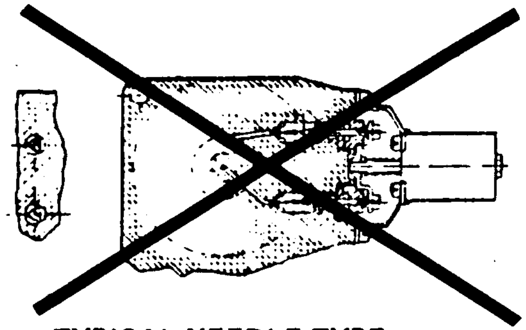
VALVE CANDIDATES

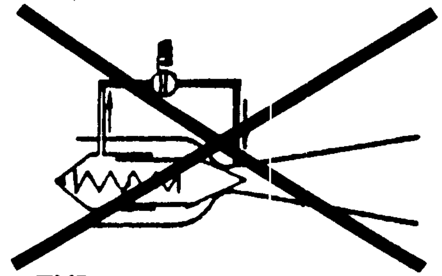
SIX DIFFERENT VALVE DESIGNS WERE EVALUATED FOR USE ON THE STBE. THE FIGURE SHOWS THE MAIN DESIGNS USED IN PAST AND CURRENT ROCKET ENGINES. FOUR OF THE SIX DESIGNS HAVE BEEN REJECTED FOR THE STBE FOR THE REASONS LISTED BELOW. THE NEEDLE VALVE WAS REJECTED BECAUSE IT IS APPLICABLE ONLY FOR EXTREMELY LOW FLOWRATES. THE VENTURI VALVE WAS REJECTED BECAUSE VENTURI VALVES OCCUPY A RELATIVELY LONG SPACE AND ARE MAINLY USED FOR FLOW LIMITATION. THE POPPET VALVE WAS REJECTED BECAUSE OF THE HIGH PRESSURE DROP ASSOCIATED WITH TURNING THE FLOW 90°. THE GATE VALVE WAS REJECTED BECAUSE ITS BULKY NATURE LIMITS IT TO LOW PROPELLANT FLOW APPLICATIONS AND IT IS DIFFICULT TO MEET NORMAL WEIGHT REQUIREMENTS.

THE BALL VALVE WAS CHOSEN AS A DESIGN CANDIDATE BECAUSE IT PERMITS IN LINE UNRESTRICTED FLOW. BALL VALVES ALSO ENHANCE STRUCTURAL SOUNDNESS FOR HIGH PRESSURE SERVICE AND CAN ALSO BE USED EFFECTIVELY FOR DEEP THROTTLING APPLICATIONS. FOR LARGE LINE DIAMETERS BALL VALVES BECOMES VERY BULKY AND HEAVY. CONSEQUENTLY THE BUTTERFLY VALVE WAS CHOSEN AS A POSSIBLE DESIGN FOR THE MAIN LOX VALVE. BESIDES HAVING A LOW PRESSURE DROP AND GOOD THROTTLING CHARACTERISTICS (SIMILAR TO A BALL VALVE), LARGE BUTTERFLY VALVES ARE EXTREMELY LIGHT WEIGHT AND COMPACT. SEALING PROBLEMS LIMIT THE USE OF BUTTERFLY VALVES FOR HIGH PRESSURE APPLICATION.

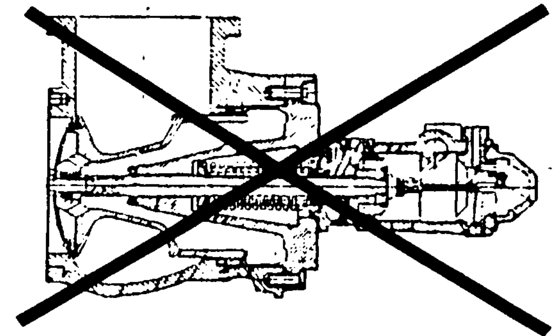
VALVE CANDIDATES



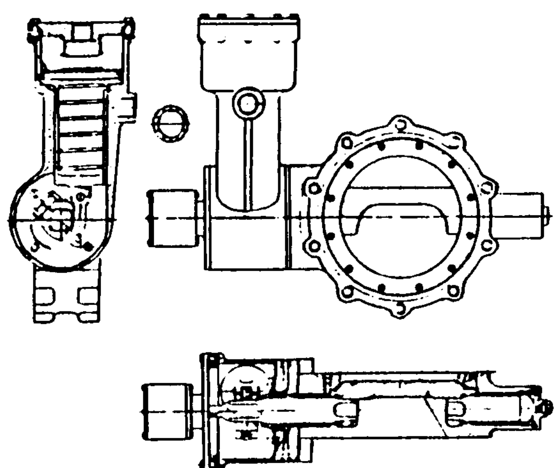
TYPICAL NEEDLE-TYPE PROPELLANT VALVE DESIGN



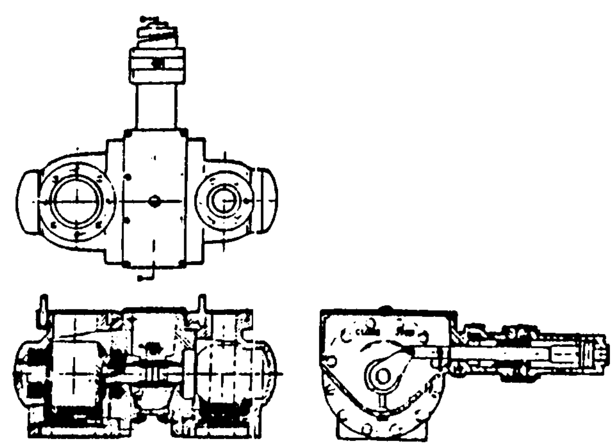
TYPICAL VENTURI-TYPE PROPELLANT VALVE DESIGN



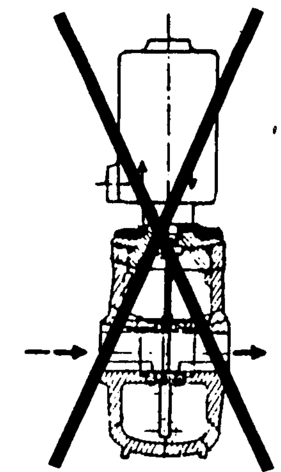
TYPICAL LARGE-SIZE POPPET-TYPE PROPELLANT VALVE DESIGN



TYPICAL BUTTERFLY-TYPE PROPELLANT VALVE DESIGN



TYPICAL BALL-TYPE PROPELLANT VALVE DESIGN



TYPICAL GATE-TYPE PROPELLANT VALVE DESIGN

86C-9-668

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SUMMARY OF ACTUATOR CHACTERISTICS

THE ADVANTAGES AND DISADVANTAGES OF PNEUMATIC, HYDRAULIC AND ELECTRIC ACTUATORS ARE SHOWN. IN GENERAL PNEUMATIC SYSTEM HAVE TOO GREAT A RESPONSE TIME FOR STBE CONTROL BUT MAY BE USEFUL AS EMERGENCY SHUTDOWN BACKUP. HYDRAULIC ACTUATORS HAVE FAST RESPONSE TIMES AND REASONABLE POWER SUPPLY REQUIREMENTS. THE ELECTRIC ACTUATION SYSTEM IS MOST ADVANTAGEOUS BUT REQUIRES A LARGE POWER SOURCE FOR HIGH MASS FLOWRATES.

SUMMARY OF ACTUATOR CHARACTERISTICS*

ACTUATOR CHARACTERISTICS	ACTUATOR TYPE					
	PNEUMATIC		HYDRAULIC		ELECTRIC	
	ADVANTAGE	DISADVANTAGE	ADVANTAGE	DISADVANTAGE	ADVANTAGE	DISADVANTAGE
1. NEED WORKING FLUID		X		X	X	
2. NEED PLUMBING		X		X	X	
3. NEED THERMAL PROTECTION	X			X	X	
4. NEED SEALS		X		X	X	
5. NEED CONTROL COMPONENTS		X		X	X	
6. EASE OF MODULATING CONTROL		X	X		X	
7. FIRE HAZARD	X			X	X	
8. COMPATIBILITY	X			X	X	
9. RAMP RATE CONTROL		X	X		X	
10. SLEW RATE CAPABILITY	X		X			X
11. MAGNITUDE OF ELECTRICAL SUPPLY	X		X			X
12. SIZE FACTOR		X	X			X

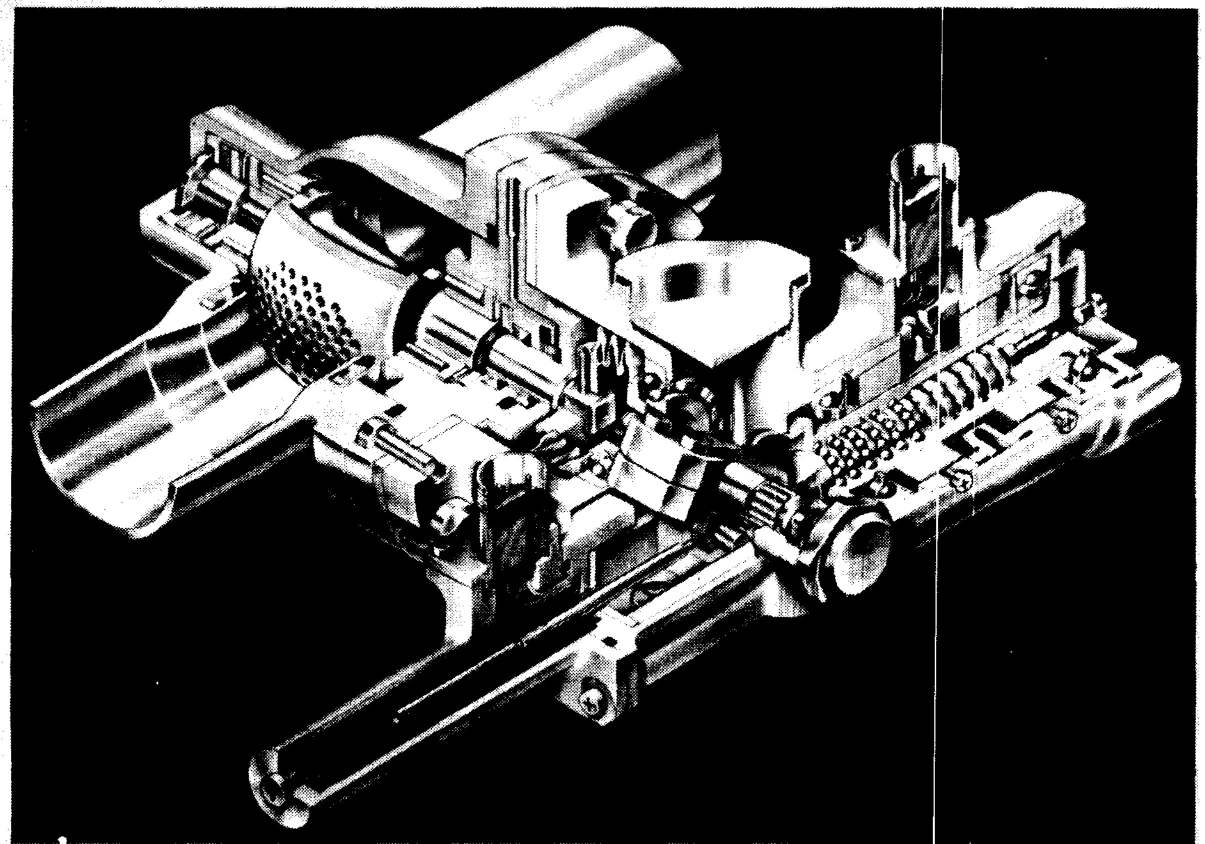
*MECHANICAL AND FLUIDIC ACTUATORS NOT CONSIDERED DUE TO COMPLEXITY AND POWER REQUIREMENTS

86C-9-669

ADVANCED ELECTRIC ACTUATED VALVE

THIS FIGURE SHOWS THE CONFIGURATION AND CHARACTERISTIC VALUES FOR A ROCKEDYNE ELECTRICALLY ACTUATED VALVE. THE ELECTRIC ACTUATOR IS MADE PRACTICAL BY REDUCED TORQUE DUE TO THE VALVE HEAD DESIGN AND A MORE POWERFUL ELECTRIC MOTOR USING RARE EARTH MATERIALS. CURRENT ESTIMATES SHOW THAT THIS TYPE OF VALVE/ACTUATOR CAN BE USED FOR ALL VALVES ON THE CANDIDATE ENGINE SYSTEMS WITH THE POISSIBLE EXCEPTION OF THE MAIN OXIDIZER VALVE. FURTHER STUDY IS NEEDED TO RESOLVE THIS QUESTION.

ADVANCED ELECTRIC ACTUATED VALVE



- TYPE – DEEP THROTTLING, LIGHTWEIGHT, QUIET FLOW, SECTOR BALL VALVE WITH LINE REPLACEMENT ELEMENTS
- LINE SIZE – 1¼ INCH ID
- FLUID – LIQUID OXYGEN
- PRESSURE – 2800 PSIG
- FLOW – 0.3 TO 28 LB/SEC
- PRESSURE DROP – 580 PSI MAX
- INTERNAL LEAKAGE – ≤ 100 SCIM He MAX
- ACTUATOR – DUAL RARE-EARTH ELECTRIC MOTORS WITH BALL SCREW LEVEL LINK
- CONTROL – MODULATING AT 100°/SEC WITH 0.1 DEGREE PRECISION
- WEIGHT – 6.0 POUNDS

SC491-432

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LOX/CH_4, LOX/RP-1 TRANSIENT MODEL START CHARACTERISTICS

THIS CHART PRESENTS A START TRANSIENT ANALYSIS PREVIOUSLY DONE FOR A ROCKETDYNE IR&D PROGRAM. THIS TYPE OF ANALYSIS WILL HELP DISCRIMINATE BETWEEN THE PROPELLANT COMBINATIONS AND WILL FURTHER DEFINE WHAT CONTROL LOOPS ARE NECESSARY.

LOX/CH4, LOX/RP-1 TRANSIENT MODEL START CHARACTERISTICS

CASE	TIME TO 90% Pc, s	PROPELLANT CONSUMPTION, LBS	REMARKS
LOX/CH_4 SPIN START	1.9	3115	T/C MR CONTROL (1)
LOX/CH_4 TANK HEAD	3.9	3740	GG MR CONTROL, T/C MR CONTROL (2, 1)
LOX/RP-1 TANK HEAD	1.4	N.A.	

(1) MAIN LOX VALVE THROTTLING IS NEEDED TO AVOID MAIN CHAMBER COMBUSTION ABOVE THE DESIGN MIXTURE RATIO
(2) LOW DENSITY CH_4 PRIMING PRESENTS DIFFICULTIES IN KEEPING GG MIXTURE RATIO BELOW THE TURBINE TEMPERATURE LIMIT

- TASK
  - IR&D EFFORT TO COMPARE POSSIBLE BOOSTER ENGINE START SEQUENCES
- RESULTS
  - HELIUM SPIN IMPROVES THE LOX/CH_4 ENGINE START
  - SPIN START WILL SHORTEN THE ENGINE START TIME AND IMPROVES PERFORMANCE

86C-9-679

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CONTROL SYSTEM FINAL CONFIGURATION SELECTION

AFTER THE DISCRIMINATORS HAVE BEEN DEFINED THE CONTROL SYSTEM ELEMENTS WILL BE EVALUATED THROUGH A LIFE CYCLE COST ANALYSIS. THE OPTIMIZED ELEMENTS WILL BE COMBINED WITH THE COMMON CONTROL SYSTEM ARCHITECTURE TO PRODUCE THE OPTIONAL CONTROL SYSTEM FOR EACH CANDIDATE.

CONTROL SYSTEM FINAL CONFIGURATION SELECTION

- **UTILIZE LIFE CYCLE COST ANALYSIS TO SELECT OPTIMUM SYSTEM ELEMENTS**
  - PERFORMANCE
  - WEIGHT
  - COST
  - RISK
  - RELIABILITY/MAINTAINABILITY

RB-52

STBE CONFIGURATION STUDY
SECOND QUARTERLY REVIEW
AGENDA

- INTRODUCTION .... F. KIRBY
- TASK 1 SUMMARY .... A. WEISS
- TASK 2 STATUS REVIEW
  - SUBSYSTEM OPTIMIZATION APPROACH .... A. WEISS
  - TURBOMACHINERY STUDIES .... A. EASTLAND
  - COMBUSTION DEVICES STUDIES .... P. MEHEGAN
  - THROTTLING ON-DESIGN/OFF-DESIGN STUDY .... W. BISSELL, D. NGUYEN
  - CONTROL SYSTEM AND HEALTH MONITOR STUDIES .... R. BREWSTER
- SUMMARY .... A. WEISS

86C-9-681-8

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SUMMARY

- TASK 2 APPROACH DEFINED
- TURBOPUMP SCREENING COMPLETE FOR FOUR CONFIGURATIONS
- PRELIMINARY INJECTOR PATTERNS SELECTED
- SYSTEM THROTTLING DESIGN POINT TRADEOFF COMPLETE
- INITIAL OFF-DESIGN STUDY EFFORT COMPLETE
- CONTROL SYSTEM STUDIES IN WORK